Abstract

Water supplies have been meeting strict experiments all over the world and the tendencies of reducing precipitations and rising temperatures in the arid and semi-arid of the Middle-East region (such as Iran) aggravate this condition during the last few decades. The significant climate changeability of the area creates drought occurrences emerge regular happening in the region which make significant losses in both the environment and economy. Water supply planning is a part of complicated, interdisciplinary progressions including several stakeholders with various attractions, professional knowledge, and preferences. Proper planning needs productive Integrated Water Resource Management models that can respond these complicated troubles.

The aim of this study was to develop a structure for applicable and efficient risk control of water supplies through drought. This management structure combines hydrological, socio-economic and water organization models. The methodology has three factors: 1) the statistical possessions of drought characterisation and drought trend in terms of space-time were examined and thresholds of drought warning are evaluated to assist as drivers for control programmes. 2) A water-planning model was applied to combine water accessibility and demand and examine the reliability of the water system to deliver the water to demand sites during the normal and drought episodes. 3) The model was used to estimates the future impacts of climate alteration, through driving them with simulations from an ensemble of statically downscaled CMIP5 model for the severest scenario in the 21st century. Moreover, some potential management plans that decrease the future hazard of water shortage were evaluated. The methods were tested in a case study in the Zayandeh Rud River basin in Iran. The results indicated the important roles of both meteorological and anthropogenic elements on occurrence of drought and water shortages. Projection outcomes recommend that future temperature increases and precipitation decreases by climate alteration with increasing water demand have the possible to increase drought risks in all time ranges remarkably. The results of the study expose its relevance for combined evaluation of drought that contain a demand analysis approach and the estimation of a climate alteration scenario. Furthermore, the results show prediction of potential future climate change and future drought characterisation can aid decision makers for designing adapted drought control actions to decrease the socio-economic effects of drought reliant on the features of the system.

Dedication

To my beloved parents.

Acknowledgments

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Abbreviations

CE	Climate Explorer
CMIP5/3	Coupled model Intercomparision Experiment Phase 5/3
DSS	Decision Support System
E	Nash-Sutcliffe efficiency
ENSO	El-Nino South Oscillation
ERWA	Esfahan Regional Water Authority
ESGF	Earth System Grid Federation
ET0	Reference Evapotranspiration
ETc	Evapotranspiration under Standard Conditions
GCMs	Global Climate Models
GHGs	Green House Gases
GIS	Geographic Information Systems
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resource Management
Kc	Crop Coefficient
KNMI	Koninklijk Nederlands Meteorologisch Instituut
NCAR	National Centre for Atmospheric Research
PDSI	Palmer Drought Severity Index
R2	R squared
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
SC	Sub-Catchment
SOI	Southern Oscillation Index
SPI	Standardize precipitation Index
SRES	Special Report on Emission Scenarios

SRI	Standardize Runoff Index
WEAP	Water Evaluation and Planning

Associated Publications

Conference contributions:

- Javadinejad, S., Hannah, D., Krause, S., "Future Climate Change Modeling and Analysis for Vulnerability of Water Resources, Case study in Zayandeh Rud River Basin in Iran". Water Resources Management Within an Uncertain Climate Section: BHS 2014-17. 12th British Hydrological Society National Symposium, Birmingham, United Kingdome, 2-4 September, 2014.
- Javadinejad, S., Hannah, D., Krause, S., Vulnerability of Water Resources to Climate Change and Human Impact: Scenario Analysis of the Zayandeh Rud River Basin in Iran. Drought Hazard and Management: Challenges in a Changing World Abstract: Vol. 2014-16, Technical Report No. 19. DROUGHT-R&SPI Summer School 'Drought Hazard & Management: Challenges in a Changing World', Hermoupolis, Syros Island, Greece, 16-20 June, 2014.
- Javadinejad, S., Hannah, D., Krause, S., Crop Yield as a socio-economic impact of Drought, Case study in the Zayandeh Rud River Basin in Iran. Abstract: Vol. 19 CIGR 2014-17. 1st CIGR Inter-Regional Conference on Land and Water Challenges – Bari (Italy), 10-14 September, 2013

CHAPTER ONE: INTRODUCTION AND STATEMENT OF AIMS AND OBJECTIVES

1.1 Context and Rational

1.1.1 The state of the worlds' water resources

Water supplies have faced critical challenges in the world in recent decades (Bazza, 2002). The water resource and demand inequities result from climate change, environmental constraints, demographic dynamics, and economic improvement aims (UN WATER, 2006, Gleick, 2003);all of which created significant struggles and increasing uncontrolled pressures on water organization, from the second half of the 20th century. Although less than 1% of the world's fresh water is readily accessible for direct human usage, reduction of this invaluable supply continues without regard for the future. Due to continued failures by governments in safeguarding water supplies, combined with rising poverty and inequality, 1.1 billion people lack access to a developed water resource. Over the last century, water consumption has increased at twice the rate of population growth. (Magrath, 2007) forecasts about 1800 million people will be living in countries or areas suffering water shortages, and two-thirds of the world's population could be under water stress conditions by 2025.

1.1.2 The state of water resources in the Middle East

In the Middle East, about 6.3% of the population is currently experiencing water stress. This is verified by the Climate Moisture Index (CMI) for the Middle East, a measure of potential water availability imposed by the climate, which is about -0.5 (frequent water stress). (Institute, 2015) projects approximately 20% of the Middle East population will be at risk of water stress by the year 2025 (Vorosmarty, 2005).

About 56% of the Middle East's land mass is semi arid. Precipitation ranges from 59mm (in Arab Saudi) to 690mm (in Tajikistan). However, the mean annual precipitation is about 225 mm; this is approximately 30% of the global annual average. Therefore, the Middle East's water resources are in global terms, scarce and extremely limited (Hazell et al., 2001). The Middle East has more than 5% percent of the world's population and 10% of its land area however only receives 2.1% of the average annual precipitation and includes 1.2% of annual renewable water supplies. Renewable groundwater quantities are very restricted and non-renewable groundwater resources are endangered through overuse, or pollution. Exploiting groundwater faster than it is naturally refilled depletes aquifer reserves and reduces water quantity, which drivers seawater intrusion by osmosis (Vorosmarty, 2005, Evans, 2009).

The population of the Middle East is presently 360 million, and is projected to reach 450 million by 2025. The demand for water is projected to grow as the population rises, living standards rise and the economy grows (Issar and Zohar, 2004). Water availability in Middle East is projected to fall below $800m^3$ capita $^{-1}$ annum $^{-1}$ by 2025. This estimate of water availability is based on population growth rates and does not include the implications of climate alteration (Vorosmarty, 2005).

1.1.3 The climate, water resources and socio-economic crises in Middle East and Iran

Climate change has raised climate variability and resulted in frequent and severe drought and floods. Iran is one of the 20 top countries in the world at risk from the impact of climate alteration. By 2030, the effects of climate change will decrease renewable water supplies by 20% by decreasing precipitation, increasing temperature, growing water demand, continuing groundwater overuse and seawater intrusion into coastal aquifers (Evans, 2009, Hulme et al., 1994).

Middle Eastern emissions of greenhouse gases are high, accounting for about 10% of the world's total. The volume of these emissions differs between countries; the main generating oil states - Algeria, Egypt, Iran, Iraq, Saudi Arabia and the United Arab Emirates account for 74% of the world's total. During 1990-2004, the rise in carbon dioxide (CO_2) emissions in the region (at over 88%) was the greatest in the world. Most of that rise came from fuel burning from automobiles and electric power production, aggravated through greatly subsidized fuel prices.

According to the IPCC, from 1970 to 2004, the area experienced an uneven growth in surface air temperature ranging from 0.2°C to 2°C. It has anticipated a rise of more than 4°C during the next 15 to 20 years. Climate models project a hotter, drier and less foreseeable climate, resulting in reduced runoff of 20 to 30% in most of the Middle East regions.

The projected higher temperatures and decreased rainfall are anticipated to raise the probability of droughts. Iran's drought frequency rose from one every 10 years in the early 20th century to 2 or 3 every 10 years presently (Fattahi et al., 2016).

The main climate alteration risks in the Middle East are related to long-term extreme dryness and drought associated with large climate fluctuations (Lelieveld et al., 2012). Overuse of limited water supplies results in shortages which can have severe impact on food security. A projection shows that even an intermediate rise in temperatures will greatly influence regional water flows. In Iran river flows may decrease by 50% by the end of the century (Samadi et al., 2012, Abbaspour et al., 2009).

Regions facing regular drought effects suffer considerable water scarcities, economic losses, and harmful social consequences. Agricultural production will probably decline 21% in value by 2024, with peaks of 43% in Iran, Egypt, Turkey and Syria (Office of the Chief Economist, 2015, Alexandratos and Bruinsma, 2012). Iran needs to export 27% of agricultural products (United Nations, 2014). It has coped with the water scarcity by using groundwater, inter-basin water transfers and local community coping strategies, including rationing. Iran utilizes more water per capita than the global mean and Iranian residential water and energy markets are amongst the most greatly subsidized in the world. Iran is very varied in terms of socio-economic and political conditions. Therefore, adaptive capacity and vulnerability to climate and drought risks differ extremely within its different regions (United Nations, 2014).

1.1.4 The challenges for water resource planning and drought management

Two different tools are necessary for effective drought management:

1) A tool to measure drought characterizations in terms of spatial-temporal patterns’ analysis and to understand climate and non-climate drivers of drought.

2) A tool to measure drought impacts on water resources and water demands with regards to socio-economic elements, to make useful adaptation plans.

The United Nations Convention to Combat Desertification (UNCCD), the World Meteorological Organization (WMO), the Food and Agriculture Organization of the United Nations (FAO) and further United Nations agencies have advanced the formation of national drought policies (NDP) with a final purpose to make drought resilient societies (Liebe, 2013). One of the necessary features of the NDP is the performance of proactive drought organization systems containing valuable monitoring and early warning systems. One of the most significant parts of a proactive drought management system, drought indicators, characterize drought circumstances and assist in developing suitable reactions to reduce impacts (Steinemann and Cavalcanti, 2006). Drought indicators are applied to evaluate and measure drought. Although a drought index value is more suitable than raw data for decision-making, indicators often suffer from scarcities, such as temporal and spatial discrepancies, statistical analysis unlikeness, and operational uncertainty (Steinemann, 2003).

Some studies investigated the usefulness of drought indices to evaluate drought on a global scale (Vicente-Serrano et al., 2012) and others graded drought indices in terms of effectiveness for the calculation of drought severity (Keyantash and Dracup, 2002). However, there is still a need for more studies to compare drought indices for drought management programs (Heim Jr, 2002).

Before making adaptation plans, evaluation of drought impacts on water supplies, water demands and socio-economic parameters are necessary (Gleick et al., 2000). Drought as an extreme event of climate change can influence the hydrological cycle, via alterations in precipitation, temperature and evapotranspiration (Gleick et al., 2000).

For future water resource planning and organization during droughts , it is important to understand how a change in global climate could affect the frequency of droughts and the availability and variability of regional water supplies (Xu et al., 2005). The study of adjustment possibilities is also important to better notify water managers so they can adjust for potential influences of climate alteration (e.g. long-term water resources design). Thus, a number of studies have been performed on the links between climate alteration and water supplies for improving water and catchment organization strategies (Xu et al., 2005, Jacobs et al., 2007). Particular characteristics of water supplies are extremely sensitive to both climate and to how the complicated water systems are controlled (Gleick et al., 2000); thus, the influences of climate and water demand trend alterations should be investigated (Field et al., 2014).

Modelling appears to be the only option to address these complicated difficulties (Xu et al., 2005). Thus, the regional scale simulation of hydrological results of climate alteration continues to attract attention (Xu et al., 2005), however capable analysis of vulnerability with adjustment is hard to perform (Yohe, 2000). Just a few studies have considered the mixed influences of alterations on hydrology and on the human consumption of water (Field et al., 2014). A better incorporation is required of human and environmental risk evaluation relative to estimates of climate alteration (Wada et al., 2013). Furthermore, incorporation of water with other sectors, like agriculture and food production, is considered to be very important for researchers (Gleick et al., 2000). Almost all studies have assumed the consequences of future climate on water management systems (Barros et al., 2015) will occur under the same policies and aims as current managers (Field et al., 2014). Additional research is required to measure the non-structural organization options in the situation of an altering climate, like demand organization and water-use efficiency (Wada et al., 2013). Influence evaluations should investigate what organization can achieve; and influence on consumers and non-climatic alterations might have a bigger influence on water supplies than the climate (Wada et al., 2013).

The research gaps show:

- There is insufficient research on characterizing drought conditions taking into consideration their complex nature. Previous studies (SIRDAŞ and Sen, 2003, Bayazit and Önöz, 2005), have utilized only one drought indicator but it is now known drought characterisation needs multiple indicators (Iglesias et al., 2007). Objective 1 of this thesis is to address this shortcoming by characterising both meteorological and hydrological drought in terms of their severity, duration, and frequency by applying multiple drought indicators using historical time series and at a regional scale. Also the relationship and comparison between meteorological and hydrological drought is analysed. Only very few studies consider the effects of non-climatic factors (such as human factor) on drought and water scarcity in the river basin, this is addressed in Chapter 4.
- More research is needed specifically regarding drought impacts on surface and groundwater resources at local and regional scales in Middle Eastern areas where water scarcity and drought conditions are severe; very few studies deal with long-term impacts of droughts on monthly water demand. This thesis has also addressed

this research gap by measuring monthly water demands affected by drought conditions to understand monthly unmet demands in Zayandeh Rud basin in Iran. The lack of integration of socio-economic factors with hydro-climatology of droughts is a major limitation of the existing studies. The second objective is to evaluate the impacts of drought on water resources and on socio-economic issues to test the ability of the existing drought management framework to manage and cope with severe droughts in the case study area. The analysis includes drought impacts on deficit of discharge, groundwater storage, water demands, agriculture crop yield and farmer's income. The hydrologic model, WEAP, is used as a tool for analysing integrated water resource management. The impacts of droughts on water supply and on water users are described; including human impacts on flow reductions during the drought years. Reduction of crop yield and its impact on farmers' income in the basin have been analysed to assess the socio-economic impacts of drought events on agriculture.

- Tools for future climate change need to be developed to improve input data to predict potential future drought events and drought characteristics (even though these tools might have many uncertainties). The climate change models and the selection of the processes of the downscaling tools need to improve to aid in design of possible future climate change and the impact of climate change on drought characteristics, water resources and water demands. The third objective of the thesis is modelling future climate change using CMIP5 and statistical downscale methods. The main climatic variables of precipitation and temperature have been examined to characterise drought at the basin scale. Determination of the impact of future climate change on drought severity, duration and frequency using Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI) at the basin scale has been carried out and the results are detailed. Also in previous research the effects of humans on future hydrological drought is neglected, so to address this issue, the impact of human activities on future stream flow (runoff) to quantify anthropogenic influence has been assessed. Future (assumed) water consumption in the domestic, industrial and agriculture sectors has been used in the model and it has been compared with the conditions where only climate factors are considered.

- There is limited research to evaluate the impacts of future droughts on water resources and water demands; neither is there any future mitigation of the drought impacts using modelled adaptation scenarios. To address this gap, the fourth objective is to evaluate future adaptation plans and alternative management decisions which are adjusted to the current situations.

No known research has been done to quantify future anthropogenic use of water in a river basin or design management strategies to optimise water consumption to reduce risks of drought due to unplanned, and sometimes wasteful socio-economic uses of water. Chapter 7 discusses in depth the quantities of water that can be saved using four water conservation measures and technologies available currently.

1.1.5 Why study the Zayandeh Rud River Basin?

The Zayandeh Rud basin as an example of a basin in Iran located in semi-arid and arid areas of the Middle East was targeted for this study for the following reasons:

1) Meteorological and hydrological extreme events are common there (Madani and Mariño, 2009).
2) The Zayandeh Rud and the Gaw Khuny swamp are two significant ecosystems in the basin. According to the Convention of Ramsar the Gaw Khuny swamp as the final outflow point of the river, is an international wetland (Felmeden, 2014). Decreasing water quantity in the basin can cause a decline in water quality. Deterioration of water

quality makes an issue for the ecosystem of the rivers and Gaw Khuny swamp. So, providing adaptation plans to conserve water quantity in the whole basin can help the level of water quality in the Gaw Khuny swamp.

3) The basin has provided the basis for centuries of important economic activity, including the increasing and establishing of Esfahan itself as the ancient capital city of Persia in Iran. The region has supported a long tradition of irrigated agriculture to provide for the basin's substantial population and also for industrial demands. The basin provides approximately 20% of the country's Gross Domestic Product (GDP).

4) The region has a high population (over 4 million people) and many are vulnerable to water shortage and drought. There are some inter-basin transfers of water into the basin making it a sensitive water resource system. As it stands, (Madani and Mariño, 2009) infer the surface water resources of the Zayandeh Rud basin were overused more than three decades ago. It is therefore apparent that supply is not adequate to meet demands.

5) Internal change and activities ongoing in the basin presently affect the water availability in the Zayandeh Rud basin specifically during drought periods. Therefore, an additional uncertainty of climate alteration (particularly decrease snowfall and rainfall and increase temperature and evapotranspiration in the basin) has high potential to upset this balance. Also because snowpack decreases and most precipitation in the basin fall as rainfall due to climate change and also high water abstractions, so it causes increase vulnerability of significant water shortage.

6) No known study of this nature has been carried out in this region, apart from that of (Raziei et al., 2009) which investigated spatiality and temporal variability of drought and water shortage in Iran.

1.2 Aims and objectives

The purposes of this study are:

1) To build up a methodological system that reacts to the interdisciplinary approach containing hydrological, agricultural, socio-economic and environmental factors in one scheme.

2) To use improved mechanisms to estimate different types of droughts and climate alteration control actions on the basin's scale.

3) To improve a model capable of simulating the impacts of drought and human water demands.

4) To fill the gap between future environmental stresses (i.e., drought and climate alteration) and future human factors (i.e., preferences of use and demand control) with regard to the improvement of future drought control strategies in the basin.

Particular objectives of this study:

1) Characterization of the organization units. Recognizing physical and management features necessary for incorporated planning, adapted to the specific conditions of the unit.

2) Characterization of meteorological and hydrological drought using different drought indicators used in the historical climate series for the study area, and choosing the benchmark for drought recognition. Also, measurement of the severity, duration, and frequency of the drought and consideration of causes of historical droughts, including large-scale climate, basin climate and some examples of human activities which influence water scarcity and drought in the basin.

3) To design conceptual model associations to integrate the water sector model (semi-distributed hydrological model with dry years' scenario, and socio-economic aspects of agriculture). Application of the models to obtain the impacts of droughts on the water supply and water users, and also the human impact on flow reductions during drought years. The

model will be used to assess the socio-economic impacts of drought on agriculture in the basin. Results will be used as input values for the integrated water management model to test the ability of the existing drought management framework to manage severe droughts.

4) To examine the main factors of future climate change variables (precipitation and temperature) and compare them with historical data on the basin scale to quantify the impacts of climate change on drought without adaptation plans. Also, the contribution of human withdrawals of water versus climate impacts on the future stream flow (runoff) is assessed to quantify anthropogenic influences on stream flow.

5) To assess the use of an integrated water management model to evaluate the potential of adaptation strategies to decrease the effects of future drought on water supplies and human water demands, and for evaluating the significance of climate and anthropogenic factor changes on water resource management.

1.3 Thesis organization

The thesis shows a comprehensive and up-to-date contribution to recognizing the relationships between climatic conditions, drought characterization, water resources and water demands management. A conceptual diagram that links together the key process considered in this research is shown in Figure 1.1.

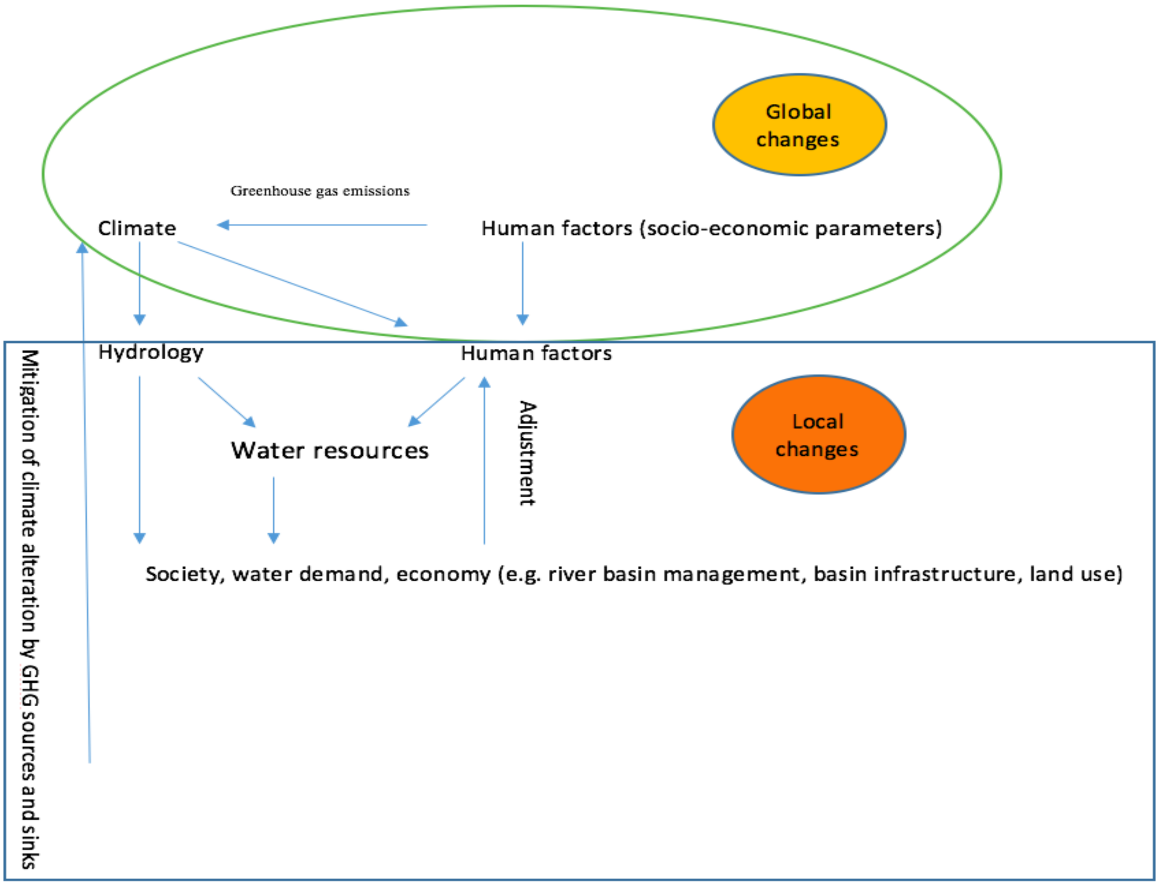


Figure 1.1: A conceptual diagram that links together for key process that this research is considering

The study takes into account other non-climatic effects on drought and water shortages. Additionally, this research provides the first estimate of the risk of future climate alteration impacts on drought characteristics in the Zayandeh Rud river basin; applying an ensemble of simulations from the most recent state-of-the-art GCMs that contributed to CMIP5.

The thesis is divided into eight chapters as shown in Figure 1.2.

Chapter 1 presents a brief overview of the research context, research aims, objectives and the scientific need to conduct the study. Chapter 2 provides a review of the literature on drought management, drought characterization, hydrology, integrated water management simulation models and climate change projection that can affect drought risks. Chapter 3 provides details of the region under investigation, descriptions of all the data and the methods used. Chapter 4 discusses drought characterizations, drought trend analysis by statistical methods and considers important causes of historical droughts including large-scale climate, basin climate and examples of human activities which affect water scarcity and drought in the basin. Chapter 5 presents an analysis of drought impacts on water resources and water demands by simulating the water allocation model in the Zayandeh Rud river basin. Also, socio-economic impacts of drought are estimated in this chapter.

Chapter 6 indicates the results of modelling future potential climate influences on drought characterization. The model is specifically designed for climate change and the ensembles of climate model simulations from GCMs that participated in CMIP5 are provided. Chapter 7 shows future potential impacts of drought on water supplies, water demands and reliability of the water system with and without adaptation scenarios. The final chapter provides a summary of findings, limitations, recommendations for further research, and suggested applications of the research.

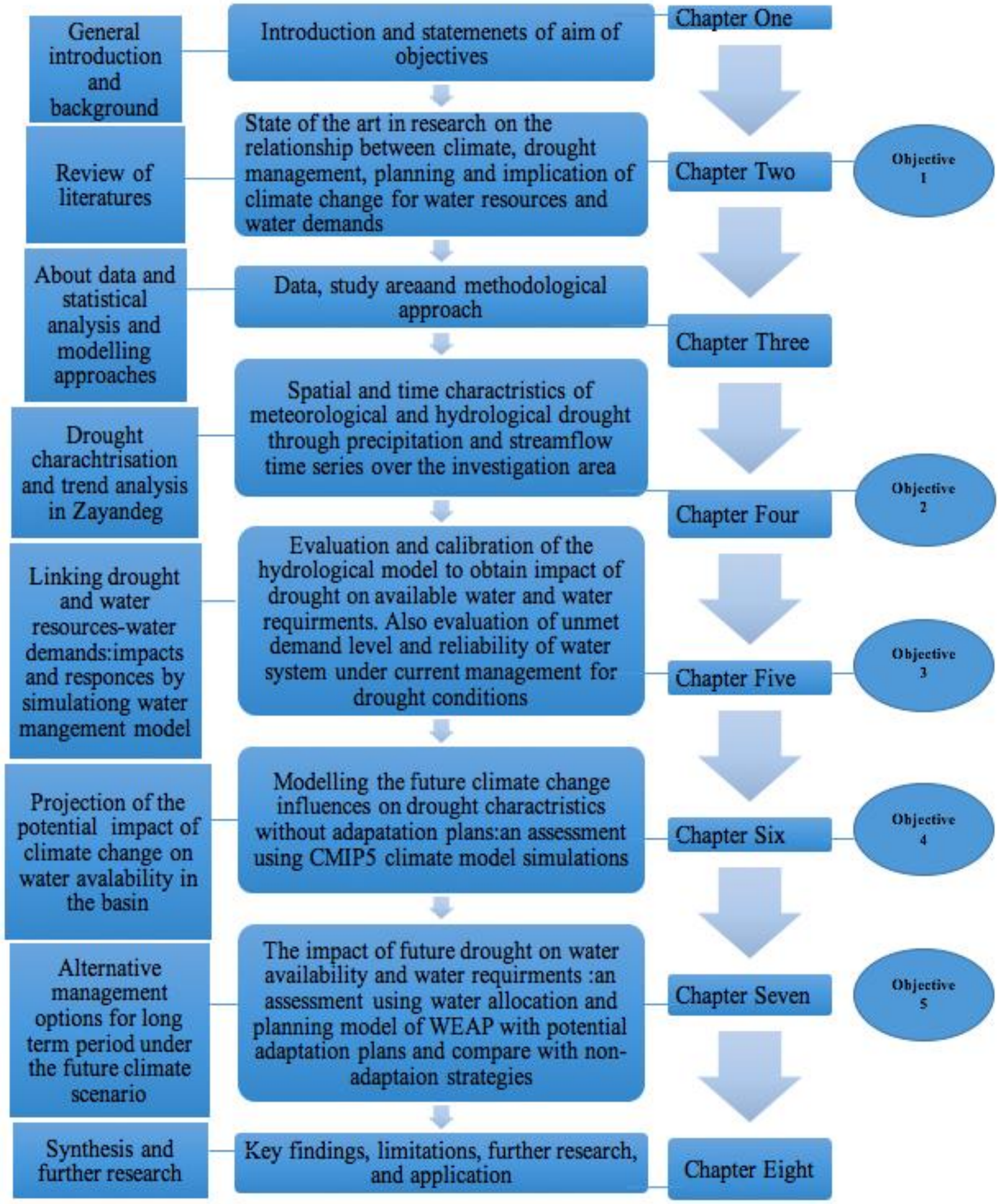


Figure 1.2: The thesis structure: Chapter context and objectives

CHAPTER TWO: LITERATURE REVIEW: DROUGHTS, DRIVERS, IMPACTS AND THEIR MANAGEMENT

2.1 Introduction

This chapter undertakes a literature review to recognize research gaps for exploration. The review is split into six parts:

(1) A summary is given on drought concepts and definitions.

(2) Drought characterization and differences between them are reviewed.

(3) The main drivers which create drought in arid regions and specifically in Iran are discussed.

(4) Drought impacts, vulnerabilities in the world and in Iran are identified.

(5) Some possible options to mitigate the drought impacts are analyzed.

(6) Requirement for some analysis tools which are compulsory for integrated water resource management for drought periods is explained.

(7) Presentation of the research gaps identified and the corresponding objectives to be addressed in the thesis.

2.2 Drought perceptions and explanations

Drought can be either a common or unusual characteristic of climate (Okorie, 2003). Drought happens in any climate with differing aspects from area to area (Wilhite et al., 2000b). Discovering an usual explanation for drought is not easy because no two droughts have the equal intensity, extent, duration or effects (Rouault and Richard, 2003).

Different studies have attempted to make a common description. There is no entirely agreed description of drought (Wilhite et al., 1992); its variations are regional and ideological.

A few developed works of literature made definitions of drought which related to the system impressed through it: meteorological drought, agricultural drought, and hydrological drought. The literature reviews on drought classification depend on the perceptions and explanations of the "National Drought Mitigation Centre" (Wilhite et al., 2014).

Different drought events usually can continue as a general evaluation progression that indicates various influences on water scarcity. The initial recognition of drought might be useful in producing control plans that decrease the influences and prevent water consumer competitions in the hydrological scheme(Okorie, 2003).

2.2.1 Meteorological, agricultural and hydrological drought

The national estimation process of drought begins with declining precipitation compared to the historical average that is followed by rising temperature, generating a dry environment, concluding in a rising of evapotranspiration, decreasing penetration and groundwater restore; this is known as meteorological drought. If rainfall decreasing remains, it may cause significant decreasing in soil water which causes water stress in plants and a decrease in crop fertility. The final phase of drought estimation is hydrological; while precipitation declining extends over time to influence hydrological systems. Hydrological drought can cause decreasing streamflows, declining reservoir storages and change the natural regimes of wetlands. All different steps of drought may have various impacts on economic, social and environmental parameters (Tallaksen and Stahl, 2014). Figure 2.1 shows the development of drought, and the link between meteorological, agricultural, and hydrological drought. Economic, social and environmental influences are displayed individual the time range, representing that the influences may happen throughout a drought at each step (Wilhite et al., 1996).

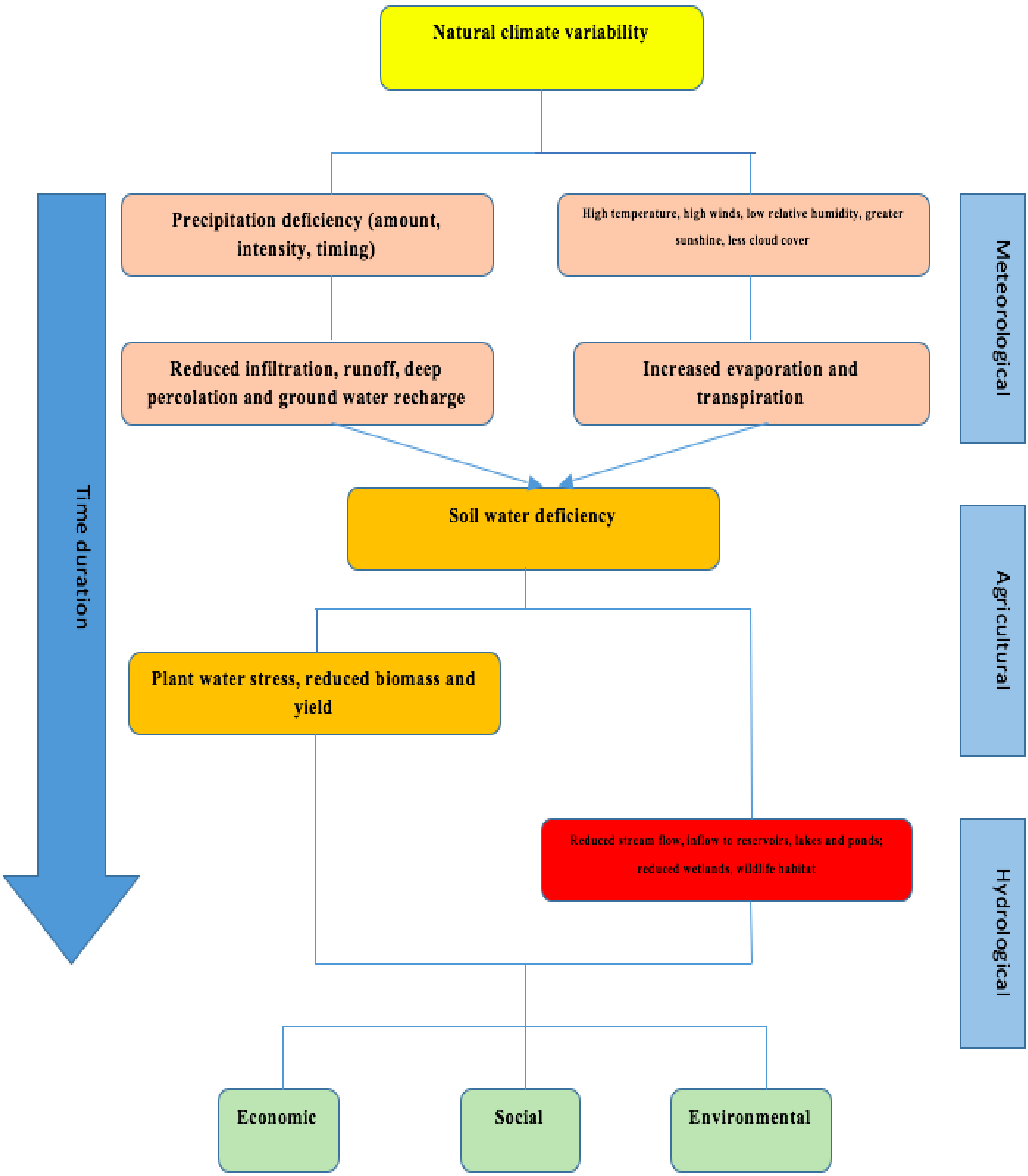


Figure 2.1: progression of drought, and the link between Meteorological, Agricultural, and Hydrological Drought and their impacts (modified from (National Drought Mitigation Center: http://drought.unl.edu/DroughtBasics/TypesofDrought.aspx)

2.3 Drought characterization

Droughts can be characterized via their beginning, severity, period, frequency and geographical magnitude; which can be assessed by statistical methods using historical data on precipitation and additional applicable variables like streamflow(Moneo Laín, 2008). The key restriction of statistical examination is the low number of drought episods happening. Although methods of analyzing the reappearance of other kinds of extreme occurrences, such as floods, are described properly; the methods to examine drought are more a specialty because of their temporal and spatial features and their relations to standardized structures of hydrologic. As the effects of drought are various and based on the continuing management and alleviation actions, only one indicator may not be enough for analysis (Iglesias et al., 2007, Moneo Laín, 2008).

2.3.1 Drought indices

Drought indices can define the current state of the climate or water supplies. The significant advantage of drought indices is their capacity to make comparisons between various regions or terms (Flores et al., 2003). The evidence generated by indices can be valuable for the examination of historical occurrences of drought, the possibility of reappearance, and for organisation and adaptation (Wilhite et al., 2000b).

A difference between some common indices, their applicability and data availability and their comparative strengths and limitations are shown in Table 2.1.

Table 2.1: Meteorological, ageicultural and hydrological drought recognition indices

	Description and use	**Advantages**	**Limitations**
Meteorological drought indices			
Standardized precipitation index (SPI)	Depend on precipitation possibility for each time scale. Used in a lot of drought management plans.	It can measure for all temporal scales drought, assistant early warning and evaluation drought intensity. Valuable for comparison between areas.	Always precipitation distribution can not be normal.
Deciles	The easy evaluation method is classifying precipitation and deciles. The Australian Drought Watch System Used it.	Easy statistical estimation. Homogeneity in drought categorization	Long historical data series needed for accuracy
Palmer Drought Severity Index(PDSI)	Soil moisture algorithm for uniform areas. Applied in the USA for emergency planning	One of the most popular indices that are significantly useful for estimation of agricultural drought, since it contains soil moisture	Complicated estimations are needed, and data requirements are not always available. Not useful for all orographic circumstances. Classification of the index based on spatial and temporal occurrences
Agricultural drought indices			
Relative Soil Moisture (RSM)	RSM is estimated the water balance from several methods. Takes climate, soil, and crop variables containing potential ET and precipitation; soil physical properties; and crop features and crop management practices (Sivakumar et al. 2011). Reported in percentage.	quantifiable and simulated, expressing how much accessible water in soil for crops	with a poor representativeness on spatial, can not be applied to paddy field
Crop Water Deficit Index (CWDI)	CWDI is based on actual evapotranspiration precipitation and irrigation demands and weight coefficient	to judge if precipitation and irrigation could meet the water need of crops or not	unmeasured, can't express other factors influence on water utilization and with various coefficients. It needs daily data

Table 2.1: Continued

	Description and use	Advantages	Limitations
Hydrological drought indices			
Standardized Runoff Index (SRI)	Similar to SPI but it used for hydrological parameters of a given area	appreciated for the region that has naturalized streamflow observation data or calibrated runoff simulations, It can establish with independent on climate, where seasonal forecast expertise is low.	It depends on observed or modeled runoff that cannot be proved everywhere
Reclamation Drought Index (RDI)	Estimated in the river basin, contributes with temperature, precipitation, snow, streamflow and reservoir levels.	It considers evapotranspiration by the contribution of the temperature.	Analyzed for each river basin related to the organization. There is a restriction for comparison capacity.
Surface Water Supply Index (SWSI)	Improved from Palmer Index which consider water accumulated as snow pack	Shows surface water circumstances which also contains water management. Contribute with hydrological and climatic characters.	Analyzed for each river basin which based on management, there is a restriction for comparison capacity. The index can not show extreme events accurately

2.3.2 Previous research on drought characterization in the world

Many studies have investigated drought (Mariotti et al., 2013, Sepulcre et al., 2012, Trnka et al., 2009, Livada and Assimakopoulos, 2007, Shiau and Modarres, 2009). Most of the studies used only a single drought indicator in large scale (e.g. global or continental or country). For example (SIRDAŞ and Sen, 2003, Bayazit and Önöz, 2005) used the theory of runs to estimate hydrological drought in Turkey and Eurasia.

However, drought forecasting tools containing multiple aspects of drought and examine the relationship between drought characterizations at small scale (e.g. regional scale) are inadequate. Since the selection of indicators and triggers should be based on regional hydro-climate circumstances (small scale), data available for long term periods is not enough.

2.4 Drought drivers

Drought can be caused by a number of elements (direct and indirect factors). The most important factors are listed below:

A) Direct drivers:

2.4.1 Lack of precipitation and high evapotranspiration

When amount of evapotranspiration surpasses the amount of rainfall stock significantly, the drought event can happen in the basin. Specially when soil dry (due to lack of precipitation), water accessible for plants to transpired into the atmosphere is fewer, so increase of evapotranspiration casue drought in Iran.

2.4.2 Increasing water demand due to urbanization, industrialization and the growth of agribusiness

Competition for freshwater occurs and it is anticipated to rise as water demand continues to rise, together with population increases and economic improvement. These two processes can define the relationship between water resource and water demand to a much greater degree than climate alteration (Vörösmarty et al., 2000).

By 2025, 1.8 billion people will live with water shortage, and by 2030 about half of the world's population will live in areas with great water pressure (Water, 2007).

The global annual water requirement has increased since 1960, and is growing by 64 billion cubic metres per year (Seckler, 1998). Some developing countries in the Middle East, even with water scarcity are large exporters of agricultural crops. For example, Iran exports 150000 tonnes of wheat and potatoes per year (FAO, 2013). To gain economic development, competition for using water resources is rising,

Industrial water consumption tends to rise with relative wealth. It can increase from less than 10 percent of total national demand in low- and middle-income countries to approximately 60 percent in high-income countries (Seckler, 1998).

B) Indirect drivers

2.4.3 Climate change

Individual drought episodes can be recognized as discrete weather events. Global climate change can cause alterations in both precipitation and temperature. For example, the frequency and duration of drought has risen in arid and semi arid lands such as the United States, Australia, Africa and some parts of the Middle-East (Dai, 2013).

One precipitation-associated driver of drought is the concentration of the year's precipitation into fewer heavier downpours, as in the United States. Heavier downpours mean that moisture is more likely to discharge as runoff rather than penetrating in the soil. Other precipitation trends that cause drought are related to latitude and current local circumstances. Climate change is projected to cause dry regions to become drier, especially in the western U.S., Australia, Africa and some parts of the Middle-East (Collins et al., 2013). Iran as an historically dry area, has experienced severe drought in the last decade (Golian et al., 2014).

Climate change may raise evaporation from the soil (Sherwood and Fu, 1997) and produce the early melt of snow in the spring in some arid areas such as the western U.S. Early melt and greater temperatures mean that by the hottest part of the summer, the water may be gone and drought circumstances become established.

Turkey, Lebanon and Iraq have experienced drought exacerbated by loss of the snow pack (Barlow et al., 2015, Bou-Zeid and El-Fadel, 2002). In 2011, Syria experienced drought conditions worsened by record heat waves and high temperatures that dry out soils (Medany, 2008). The extreme drought in Iran during the last decade was affected by all of these impacts: low precipitation, low snowpack, and high temperatures.

Future climate change and future drought can be predicted by Global Circulation Models (GCM). So improvement in GCMs' output by decreasing errors can help to produce better future drought projection and mitigation plans.

2.4.3.1 Research related to climate change in Iran

Very few studies on climate change in Iran have been carried out (Rafiei Emam, 2015, Ashraf Vaghefi et al., 2014). For example, (Gohari et al., 2013) provided data to improve regional climate change scenarios. The scenarios were generated from a global climate model driven by the A2 and B1 SRES socio-economic scenarios and downscaled for the area. Then the resulting high-resolution scenarios were applied to derive effects of climate change in agricultural production. The timeframes studied were 2015-2044.

Another study focused on the evaluation of the impacts of climate change on water resources without highlighting the importance of seasonality in river flows. The rise of temperatures and decline of precipitation will create less accumulation of water as snow, leading to lower flows in river resources. The climate change scenarios were generated from a random global climate model (CGCM3.1 provided by Canadian Global Coupled) and driven by the A2, B1 and A1B SRES socio-economic scenarios. The model provides simulation for the period (1980 – 2000); future timeframes contemplated are 2013-2039 and 2073-2099 (Emam et al., 2015).

The consequences distinguished from the model must be explained since only one model from the SRES scenario is not sufficient. Also uncertainties in model performance have to be considered, and the results should be interpreted and analysed.

2.4.4 Weak or ineffective drought management

Some arid regions such as Africa, and some parts of the Middle East like Iran have weak or ineffective drought management capacities to address drought risks, (Wadid Erian (Ed), 2013).

Progress is being made in drought risk management; in predicting, early warning, preparedness, reaction and the improvement of compensatory mechanisms such as insurance and temporary employment programmes (Rached, 1996).

2.4.4.1 Drought management in Iran

For Iran, there is no legal framework for facing drought risk, and there are no emergency actions referring to natural disasters (Samimi and Samimi, 2012). Recent droughts have shown the inadequacy of the legal systems, and losses in agriculture. Iran is unsuccessful due to the lack of management of water at the basin level and lack of coordination of policy, physical and technical aspects during droughts.

2.4.5 Previous research on drought drivers in the world

Some studies revealed that climate change in large scale will likely impact future meteorological and hydrological drought characteristics across the world (Arnell, 2008). For example, (Klönne, 2012) focused on the effects of climate change on meteorological drought in Africa by using AGCM. Also (Yu et al., 2012) evaluated climate alteration effects on meteotological drought in Europe by using CMIP3.

Also some studies have attempted to understand the drought risk policy as a drought driver (Wilhite et al., 2014). For example, (Daniell, 2012) analysed the effects of poor policy and legislation on water using (by using interview and workshops) which causes hydrological drought in Bulgaria. However, estimations of the impact of all human water uses on deficit of stream flow and hydrological drought have been neglected.

2.5 The impacts and vulnerability of drought in various sectors

Drought affect further people than any other natural hazard and it can occur anyplace over the world (Wilhite et al., 2000a). The complication of drought effects relates to the significance of water for, domestic, agricultural yield, and domestic, as well as for the hydropower and recreation, navigation and reduction of sewage (Moneo Laín, 2008) . The impacts can be either direct or indirect, regulated by the temporal and spatial range of their happening (Heim Jr, 2002, Moneo Laín, 2008).

Drought may disturb extensive regions and produce great social difficulty, economic deficit and environmental destruction and occurs across months and years. Most economic effects happen in forestry, agriculture and fisheries because these sectors depend on surface and subsurface water resources (Eriyagama et al., 2009) (Lloyd-Hughes and Saunders, 2002). Drought impacts are a function of the severity of the event. For example, the National Drought Mitigation Centre notifies about starvation associated with drought, usually in African areas instead of other reasons like war or civil strife (NDMC, 2005). In Africa, some initial cautionary systems made to display physical and social variables that indicate food anxiety. For example the Southern Africa Development Community (SADC), displays the food and crop condition in the area (NDMC, 2005). The following parts explain the most common effects of drought in various socio-economic sectors. In some situations, the impressions appear in districts outdoor the regarea suffering drought. For instance, drought influence on urban water resource might be a result of rainfall reductions in the district where the storage is placed, and not in the area of the urban. In many associations, the effect of drought on a disturbance in the water resource structure is severe . When the volume of streamflow is lower, water inflows to reservoirs may be of lower quality because of further consolidation of nutrients or pollutants (Moneo Laín, 2008).

Drought conditions may cause the need for pricey crisis actions to relocate water from a basin or hydrological structure to another (Esfahan regional water authorithy, 2003). It may become compulsory to confine resources through parts of the day in severe circumistances, like resources to Karkhe in south of Iran during the drought event of 1992-1993.

2.5.1 Incidental effects and various pressures

The previous section defines direct impressions of drought; but, there are additional effects that can be identified as indirect. For instance, the direct influence of drought on agricultural or forestry production can influence on the agricultures' earnings, and the related agribusiness as well. A number of the effects can appear in the short period. Alternative environmental impressions remain for part of a period or maybe turn into constant. For instance, nature habitation might be displaced by the damage of vegetation, reservoirs and swamps. The declining of environment quality, containing intensified soil deterioration, can produce a further constant damage of biological yield (Moneo Laín, 2008).

Indirect impacts may even cause migration movements that depend on the intensity of drought (Wilhite et al., 2000b). Drought effects have not been measured cost-effectivaly properly, so, executives are likely to minimize the significance of drought. Climate in the Middle East has a constrained capability to protect the environmental results of alterations in land usage (Bates et al., 2008, Moneo Laín, 2008). The capability particulary is smaller in semi-arid zones such as Iran, where rainfall is significantly changeable in time, space, volume and period (Ghasemi, 2013, Saeedipour and Moradi, 2011).

2.5.2 Previous studies on drought impacts in the world

Howitt et al. (2014) estimated economic impacts of drought in the year 2014 in California by using a SWAT model. Another example, Vicente Serrano et al., 2012, estimated drought impacts on vegetation activities on a global scale using SPEI for the years of 1981-2006.

In the field of hydrology, some studies investigated the impacts of drought on surface water resources (Hagemann et al., 2013). For example, (LENNARD et al., 2014) estimated drought impacts on surface water quantity and quality in the UK by using a rainfall-runoff model (HYSIM) for 1880-2012. Christensen and Lettenmaier, (2007) estimated drought impacts on future water resources using Colorado River Reservoir model (CRMM) and 11 ensembles of

GCM models under two emission scenarios A2 and B1. However, more research is needed regarding drought impacts on both surface and groundwater resources; and the vulnerability of water use sectors and the uncertainties associated with the description of drought events. Spatial and temporal characteristics and assessment of drought are only meaningful if they are integrated with socio-economic factors.

2.5.3 Climate change impact studies in Iran

Semi-arid and arid areas such as Iran are illustrated by an unbalanced natural geographical distribution of rainfall and water bodies, water availability and insignificant sustainability in water consumption. This can be aggravated by climate change, which has the potential to influence water availability and reliability, food security, energy and the environment. (L'vovich, 1979, Arnell, 1999) mentioned the present water resource management procedures are not sufficiently placed to act with the effects of climate change.

According to (Motiee et al., 2001) current policy and associated decision making for water resource management in Iran are not respected because of uncertain climate change and the hydrological cycle intensifies with any alteration in climate (Muller, 2007). As Iran is already under water stress in some areas, it presents a serious situation and the capability to adjust to these alterations is weak; integrating this risk into existing day policies is urgently needed.

The latest published research on climate change influences in Iran was commissioned by the Water Research Commission in 2002 and was carried out by a local university. The study is entitled *"Climate Change and Water Resources in Iran: Potential Impacts of Climate Change and Mitigation Strategies"* (Schulze, 2005b). The study developed plausible climate change scenarios for Iran using the Conformal – Cubic Atmospheric Model (C-CAM) by simulating the period 2070 – 2100, compared to 1975 – 2005. Then, it investigated the potential impacts of climate change on hydrological responses and water resources, however, adaptation plans were not determined.

2.6 Drought mitigation options

Activities in the long and short term can be applied to avoid and decrease drought effects and develop drought planning and response attempts. The description of drought management actions contains: 1) preparation, early warning, monitoring systems; 2) creating priorities of water consumption; 3) expressing the circumstances and the thresholds to announce drought stages; 4) determining the management purposes in each drought stage; 5) describing and fulfilling the actions.

Future drought management has not received adequate attention within natural hazards' research; compared to hurricanes and floods which have direct and immediately visible influences. A few countries, regions and communities, presently manage future drought risk within reactive, crisis-driven approaches. In a pro-active approach, early warning systems are significant as they are main factors in integrated risk evaluation, interaction and decision support systems of drought information systems (Pulwarty and Sivakumar, 2014). Effective projection of the impact of climate change on drought characteristics depend on projection and evaluation of climate change variables (Bhattacharya et al., 2004). However, future possible climate change monitoring and evaluation, which link to future climate change impacts on drought characteristics and water resources, are too uncertain and have insufficient techniques for downscaling (Sheffield and Wood, 2008, Burke and Brown, 2008). Table 2.2 summarises drought management actions. The table shows a range of long-term and short-term actions, divided into the three groups of water supply rise, water demand decrease and drought effects mitigation (Rossi et al., 2007, Iglesias et al., 2007).

Table 2.2: Short and long-term drought mitigation actions

Class	Kind of actions	Affected segments
Short term actions		
Water resources rising	Development of the efficiency of current water system (alternative operating rules, discover leaks in the system)	Urban, agricultural, industrial
	Rising groundwater abstractions	Urban, agricultural, industrial
Demand reduction	Rising public awareness for water saving	Urban, agricultural, industrial
	Changing water use cost	Urban, agricultural, industrial
	Binding limitations	Urban, agricultural, industrial
Effects reduction	Temporary changing the allocation of water supply	Urban, agricultural, industrial
	Public assistant to reward income losses	Urban, agricultural, industrial
	Public assistant for crops insurance	Agricultural
	Decreasing tax or postponement of payment deadline	Urban, agricultural, industrial
Long time actions		
Water resources rising	Re-utilize of treated wastewater	Agricultural, industrial
	Inter- basin water transfers or outside water transfers	Urban, agricultural, industrial
	Build new reservoirs or rising the storage capacity of the current dams/reservoirs	Urban, agricultural, industrial
	Seepage supervisory and evaporation losses	Urban, agricultural, industrial
Demand reduction	Save more water	Urban, agricultural, industrial
	Agronomic method to rise irrigation efficiency and decrease water utilization	Agricultural
	Cultivate dry crops that adapted to dry conditions	Agricultural
	Increase return water and water recycling	Industrial
Effects reduction	Increase education for saving water	Urban, agricultural, industrial
	Change the allocation of water supply on water quality needed	Urban, agricultural, industrial
	Improvement of early warning system	Urban, agricultural, industrial
	Create insurance programs for water utilization	Agricultural, industrial

Although there is some research that suggests mitigation plans (Hamdy, 2012, Iglesias et al., 2007), there is no sufficient research to measure the mitigation value properly or simulate adaptation scenarios for future drought impacts and compare the different adaptation plans on a regional scale .

2.7 Tools requirement for integrated water resource management

DSS is a suitable tool for better understanding, development and proper implementing of the IWRM process. More details about DSS are explained below:

2.7.1 A decision support system (DSS)

DSS can be described as an incorporated, communicating computer system. It contains systematic tools and information organization abilities, plus a conversant systematic method to examine possibilities in answering complicated water management troubles (PARTNERSHIP, 2000). A DSS is made by three principal factors; first the data needed for the analysis is attained. This is gained through different means, for instance, hydro-meteorological from ground stations, within remote sensing technologies such as radar and satellites or from examinations and literature.

Secondly, the data is gathered into a database within the consumer collaborate, for easy access and availibilty of analysis tools and models. Examination of the data can be organized by simple spreadsheets or GIS functions (spatial representation of georeferenced data) and developed in models. Finally, the results can have the user collaborate and produce the base of decision-making. Figure 2.2 represents a schematic description of the DSS construction. Due to the multi-faceted character of IWRM, DSS can make it easier for policymakers and water managers to accomplish 'what if' scenario examinations. The analysis can at the same time deal with single or a grouping of contributing parameters: climate change, land cover, and land use change, population growth on the hydrology, water quality and economic associations in the system.

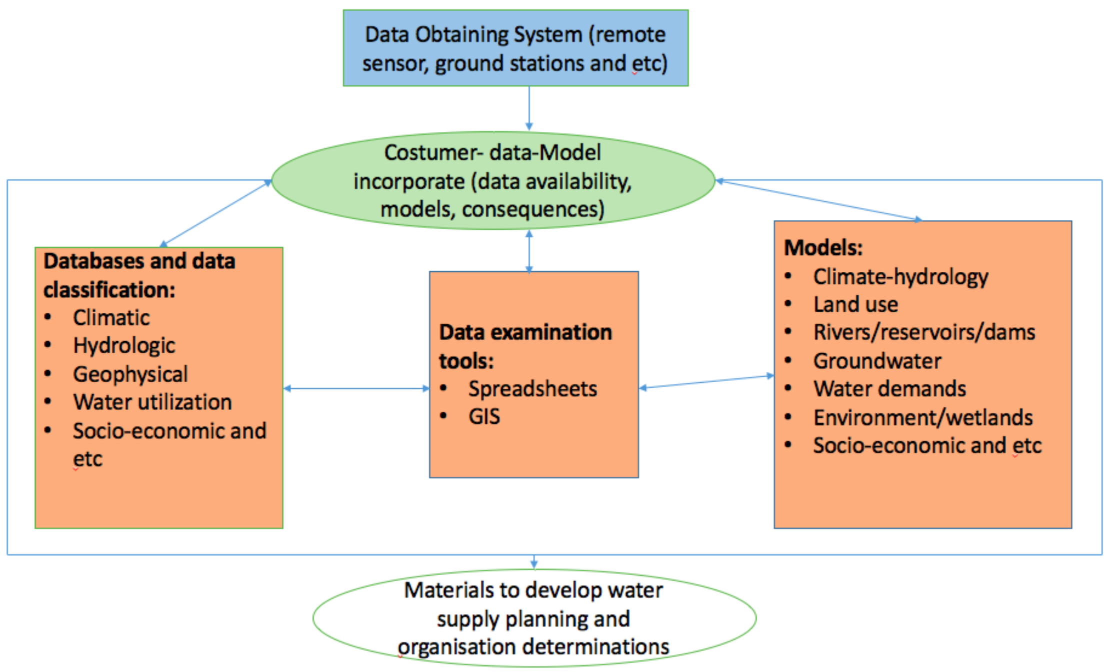


Figure 2.2: The DSS construction (Georgakakos, 2007)

There are extensive variations of DSS's, which are applied in river basins. Table 2.3 indicates some models of common applications that have been used to IWRM.

Table 2.3: Basic Decision Support Systems

Model	Established by
WEAP (Water Evaluation And Planning)	Stockholm Environment Institute (USA)
MODSIM	Colorado State University (USA)
MIKE BASIN	DHI (Denmark)
RIBASIM (River Basin Simulation Model)	Delft Hydraulics (Netherlands)
WBalMo (Water Balance Model)	WASY Ltd (Germany)
WaterWare	Incorporates between the EUREKA project EU487 and related RTD projects
MULINO-DSS (Multi-sectoral Integrated & Operational Decision Support System)	A consortium under the European Union

The WEAP model has applied in this study; so, more aspects of its organization and abilities are presented.

2.7.2 The Water Evaluation and Planning (WEAP) Model as an example of DSS

Stockholm Environment Institute's (SEI) Boston Center improved WEAP, which is a desktop tool for incorporated water resource planning. After the first appliance by (Raskin et al., 1992) for the Aral Sea area, the model has developed significantly. It has a user-friendly graphical user interface (GUI), a stronger water allocation algorithm and the incorporation of hydrologic sub-modules that contain a conceptual rainfall-runoff and a water quality model for groundwater and stream flow. Also, further coupling selections to external models, for example, Modular Three-Dimensional Groundwater Flow Model (MODFLOW) and QUAL2E water quality model are available when needed. The WEAP model is a user-friendly tool that encompasses a combined method for water resource management, which in the last decade focussed on demand management, water quality, and ecosystem conservation. The model combines both simulations of the natural and engineered factors of a water supply system through locating demand side problems. For example, tools efficiency, re-use policies, water use patterns, expenses and water allocation organizations on an equivalent balance with supply-side like surface and groundwater availability, reservoir storage and inter-basin transmissions. This gives the water manager the choice of a wide-ranging view of the results of different determinations in the system.

For this study WEAP model is selected because 1) WEAP is freely available for users in developing countries such as Iran. Also with regards to the knowledge level, practices and time availability, the model is selected. 2) WEAP allows users to make spatially based models that estimate hydrological alterations through incorporating evolving climate circumstances and human-managed infrastructure or land use. 3) In this study, most of the data required for water deep percolation and the aquifer design are not available and it was easier to calculate them at a larger scale. 4) In a WEAP model, water infrastructure and allocation can be dynamically nested within the underlying hydrological processes. So, the effects of specific infrastructure configurations, land use and priorities of water allocation for different water used can be analysed using weather data and physical watershed conditions. WEAP allocate available resources at each time step based on user defined demand priorities and supply preferennces.

WEAP is one dimensional semi-distributed model. A rainfall-runoff simulation method in WEAP is used to simulate basin hydrology. In the model the amount of rainfall that is not evapotranspired is available for infiltration and runoff. Independently of the rainfall intensity, the amount of rainfall going to runoff or ground water is specified as a percentage of the amount of water still available after evapotranspiration has occurred. Runoff corresponds to the rapid response of the catchment and is therefore directly turned into river streamflow whereas infiltrated water (slow response) goes to aquifers. More details about description of the model is in section 5.2.1 in chapter 5.

2.7.2.1 Applications of the WEAP model

In different IWRM projects with diverse objectives, WEAP has been used extensively around the world. Some examples are mentioned in the Appendix.

2.7.2.2 Applications of the WEAP model in Iran

(Yaghobi et al., 2012) used the WEAP model for the Golestan River basin in Iran to measure the capability of the Gorgan River to meet the water demands of several consumers as well as the ecological preservation. The hydrology of the basin was simulated using rainfall and naturalized streamflows only. However, the hydrology was organized by applying calculated monthly stream flows from a previous study. Hence, the streamflow simulated was not applying the various climatic and non-climatic factors in the hydrology module of WEAP. Calibration of the model was not prepared even by changing assumptions about the historic demand, changing requirement priorities and changing the operational policies of water storage dams to develop the fitting between simulated and observed stream flows.

(Abrishamchi et al., 2007) carried out another study to measure the historic scenario of water supply improvement in the Karkheh River Basin from 1988 to 1994 giving a view of how the water infrastructure improvements work in the situation of rising water demand.

Both studies above excluded the simulation of future climate change and related mitigation strategies. The effects of future climate, changes in water demand, water resource improvement and land use were not measured and were not incorporated naturally into the observed stream flow data. However, these effects are important to either increase or decrease stream flows. Although, examining of these effects either individually or in several mixtures on the hydrology are complex under this model structure.

2.8 Research gaps identified

The literature review has highlighted some research gaps which link to the research objectives of this thesis:

- There is insufficient research on characterizing drought conditions taking into consideration their complex nature (see section 2.2). Previous studies (SIRDAŞ and Sen, 2003, Bayazit and Önöz, 2005), have utilized only one drought indicator and it is now known drought characterisation needs multiple indicators (Iglesias et al., 2007). Therefore, objective 1 of this thesis is to address this shortcoming by characterising both meteorological and hydrological drought in term of their severity, duration, and frequency by applying multiple drought indicators using historical time series and at regional scale (detailed in Chapter 4 of this thesis). Also in this chapter, the relationship and comparison between meteorological drought and hydrological drought has been analysed.

- As reviewed in section 2.4.7, more research is needed specifically regarding drought impacts on surface and groundwater resources at local and regional scales in Middle East areas where water scarcity and drought conditions are severe. Very few studies deal with long-term impacts of droughts on monthly water demand. The thesis has also addressed this research gap by measuring monthly water demands affected by drought conditions to understand demands in Zayandeh Rud basin in Iran. The spatial and temporal characteristics and assessment of drought are only meaningful if they are integrated with analyses of socio-economic impacts of drought (section 2.4.6). However, the lack of integration of socio-economic factors with hydro-climatology of droughts is one major limitation of the existing studies. The second objective is to evaluate the impacts of drought on water resources and on socio-economic issues to test the ability of the existing drought management framework to manage and cope with severe droughts in the case study area. The analysis includes drought impacts on deficit of discharge, groundwater storage, water demands, agriculture crop yield and farmer's income (see Chapter 5). The chapter describes the impacts of droughts on water supply and on water users; including human impacts on flow reductions during the drought years. Reduction of crop yield and its impact on farmers' income in the basin have been analysed to assess the socio-economic impacts of drought on agriculture in this chapter.
- Tools for future early warning and monitoring systems need to be developed to improve prediction of future drought events (even though they might have many uncertainties) and this has been identified as a research gap and discussed in section 2.5). The climate change models and the selection of the processes of the downscaling tools need to improve to aid the design of future early warning systems. Prediction and analysis of potential impacts of future climate change on drought

characteristics, water resources and water demands are essential. This is particularly required for the regions where the projected climate change impacts and the effects of human factor on drought risks are both significant. The third objective of the thesis is modelling future climate change using CMIP5 and statistical downscale method (see Chapter 6). The main climatic variables of precipitation and temperature have been examined to characterise drought at the basin scale. Determination of the impact of future climate change on drought severity, duration, and frequency using Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI) at the basin scale has been carried out. Also as mentioned in section 2.3.2, the effects of humans on future hydrological drought are neglected, so to address this issue, in this chapter the impact of human activities on the future stream flow (runoff), to quantify anthropogenic influence has been assessed. Future (assumed) water consumption in the domestic, industrial and agriculture sectors has been used has been used in the model and compared with conditions when there are only climate factors to consider (see Chapter 6).

- There is limited research to evaluate the impacts of future droughts on water resources and water demands, neither are there any future mitigation of the drought impacts using modelled adaptation scenarios. To address this gap, the fourth objective is to evaluate and analyse future adaptation plans and alternative management decisions. To the best of our knowledge, no research has been done to quantify future anthropogenic use of water in a river basin and based on this, design management strategies to optimise water consumption to reduce risks of drought. Chapter 7 discusses in depth the quantities of water that can be saved using four water conservation measures and technologies available currently so that future drought risks can be minimised.

CHAPTER THREE: STUDY AREA, DATA AND CHOSEN METHODOLOGICAL APPROACHES

3.1 Introduction

This chapter details the research design of the thesis by displaying how all aspects of the research fit together; defines the characteristics of the study area and data used in the assessments; and introduces the methodological approaches adopted in addressing the research aim and objectives specified in Chapter One.

3.2 Research design

As highlighted in Chapter Two, some studies have been conducted quantifying climate-drought and water resources' relationships in America, Africa and the Middle East (McNab and Karl, 1988, Gan et al., 2015, Fattahi et al., 2016).

3.3 Study area: Zayandeh Rud basin, Iran

3.3.1 Criteria for river basin selection

The Zayandeh Rud basin located in a semi-arid and arid area of the Middle East was targeted for this study for the following reasons:

Extreme events such as meteorological and hydrological events are common (Madani and Mariño, 2009).

The Zayandeh Rud and the Gaw Khuny swamp are two significant ecosystems in the basin. According to the Convention of Ramsar the Gaw Khuny swamp, as the final outflow point of the river, is an international wetland (Felmeden, 2014). Decreasing water quantity in the basin can cause a decline in water quality. Decline of water quality makes an issue for the ecosystem of the rivers and Gaw Khuny swamp. Therefore, providing adaptation plans to conserve water quantity in the whole basin can help the level of water quality in the Gaw Khuny swamp.

3.3.2 Overview of identifying the study area

Iran is geographically diverse and has various topography with different climates. It includes the central plateau surrounded by two mountainous zones of Alborz in the north and Zagros in the west with elevation ranges of -56 to 5415 m.a.s.l. The mountains do not allow the Mediterranean moisture bearing systems cross through this region to the east (Barthold, 2014). Therefore, especially in the warm season, most of Iran including the Zayandeh Rud basin, is influenced by a high subtropical mass of air (Rahimzadeh et al., 2009). This causes the warm summer. A major part of the precipitation (about 70%) (Mohammadi-Sheshnarmi, 1998) is generated by the Mediterranean air mass that is brought in by the western winds in the cold season. As shown in Figure 3.1 the average annual precipitation for Iran is less than a third of the world's rainfall (Mansouri Daneshvar et al., 2013).

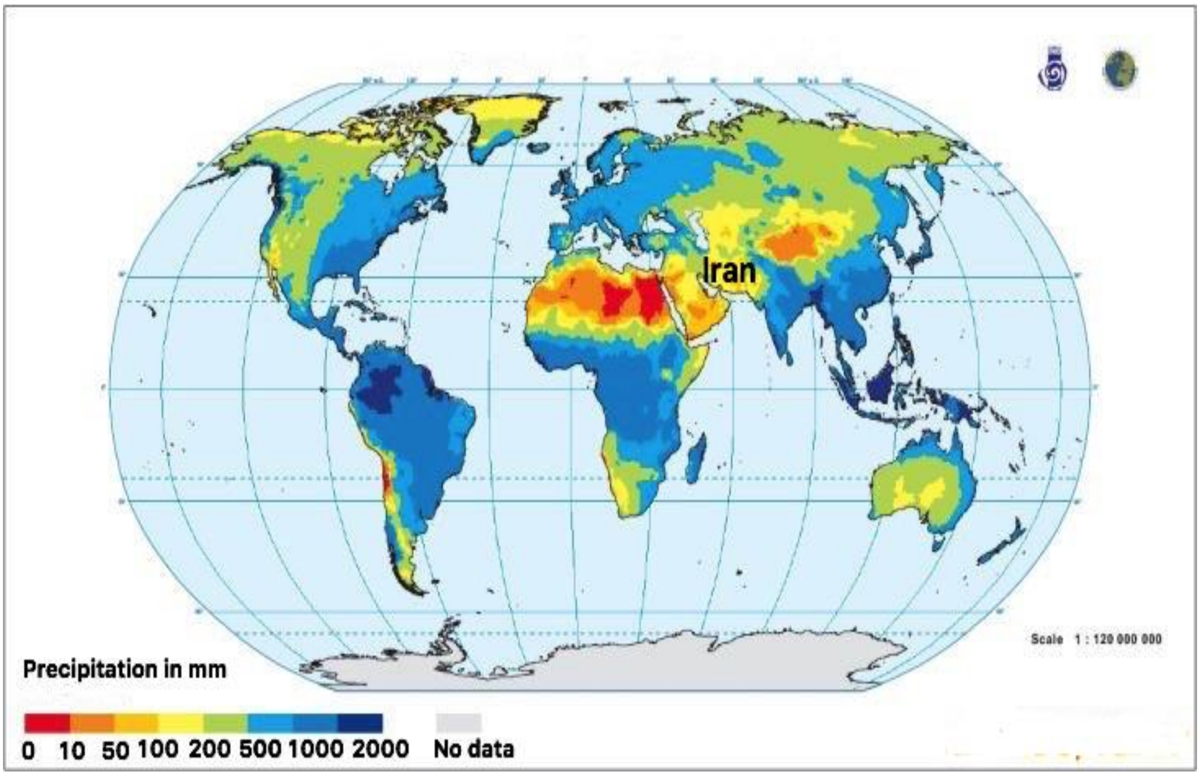


Figure 3.1: The average annual precipitation for world. (Refrence: (http://www.whymap.org/whymap/EN/Downloads/Additional_global_maps/precipitation_g.html?nn=1577156, Accessed November 2013)

The Zayandeh Rud basin is divided into 17 sub-basins, shown in Figure 3.2 and Table 3.1; each has a corresponding hydrologic unit and they are major tributaries to the main stream of the Zayandeh Rud River. The sub-basins are identified by the Esfahan Regional Water Authority. The upper of the Zayandeh Rud basin is a part of the Zagros Mountain (one of the biggest mountains in Iran) and has high rainfall. The elevation of the basin varies between 1000 to 3600m mean sea level elevation (m.a.s.l). The upstream of the basin is its main part because the main water resources are located there.

The Zayandeh Rud basin has an especially arid or semi-arid desert climate. Rainfall in most of the region, especially in the central part of the basin, for example in Esfahan-Borkhar (sub-catchment 4202) with an elevation of 1550 m, averages only 120 mm per year. The amount of the natural vegetation covering the basin depends on the amount of received annual rainfall; so there is only a small amount of natural vegetation cover, especially downstream of the basin (Morid, 2003).

As water and energy demands rise in the basin, water withdrawals from the river rise and it is critical that climate changeability is integrated into related decision-making (Salemi et al., 2000). The Zayandeh Rud reservoir supervises the upstream streamflow of the basin and is the biggest surface reservoir on the river with a volume of 1470 million cubic metres (MCM) (Esfahan Regional Water Authority). The accumulated annual average inflow to the Zayandeh Rud reservoir is around 1600MCM, of which an average annual flow of 600MCM is transferred from the adjacent Chaharmahal Bakhtiyari river basin which is shown in Figure 3.3 ((ERWA), 2011).

As there is a high correlation between streamflow and precipitation, the effect of precipitation on autumn and winter streamflow (November to March) and spring streamflow (April to June) is significant (Parker, 2010).

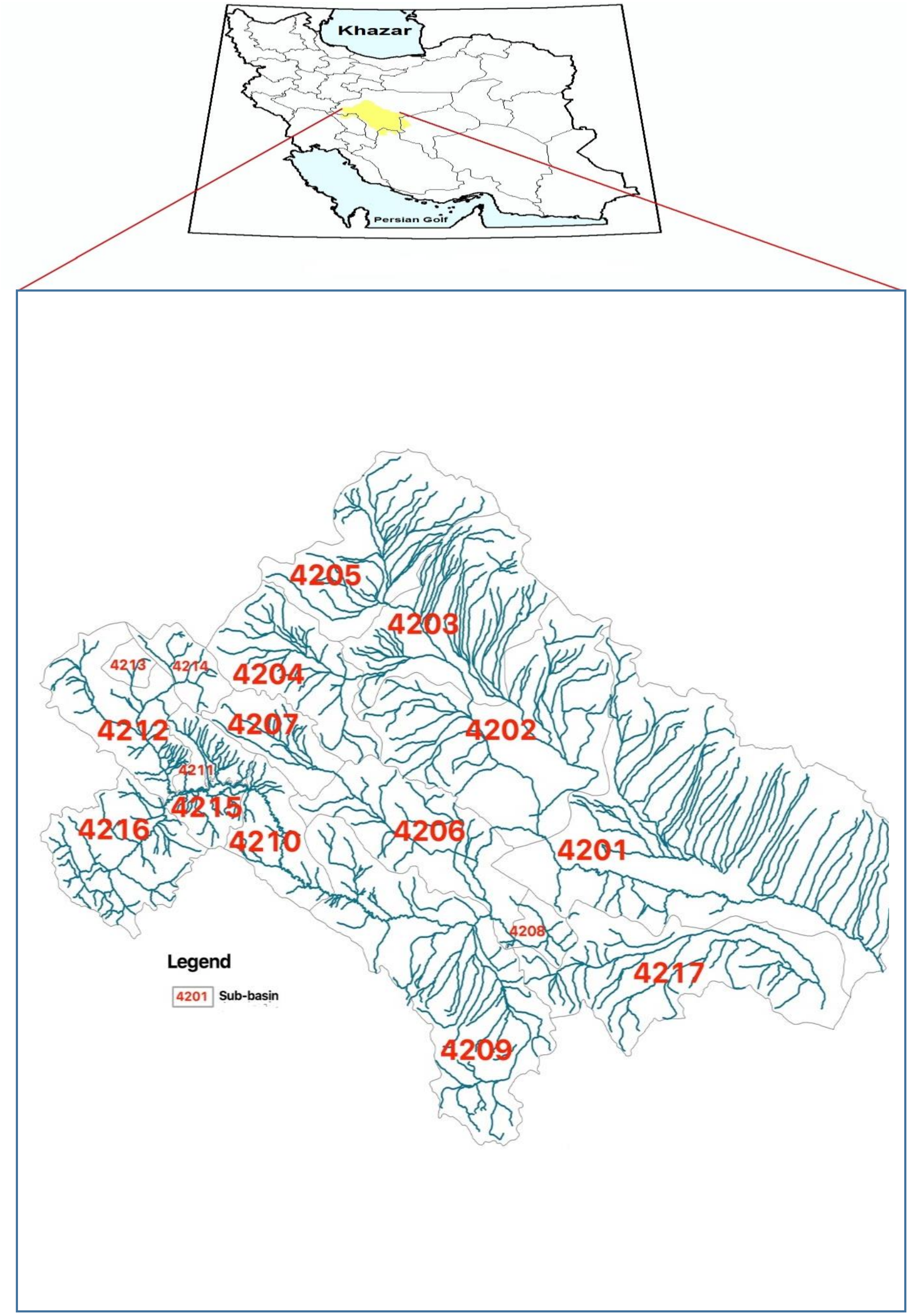


Figure 3.2: Location of the Zayandeh Rud river basin in Iran and map of the basin showing boundaries of sub-basins (Adapted from Esfahan Regional Water Authority, 2012)

Table 3.1: Sub-basins in the Zayandeh Rud basin area

Sub-basin code	Study area s' name	Area (Km^2)
4201	Kohpaye-Segzi	6819
4202	Borkhar-Esfahan	3473
4203	Morchekhort	2287
4204	Alavije-Dehagh	1472
4205	Meymeh	2098
4206	Najafabad	1730
4207	Karvan	729
4208	Mahyar	283
4209	Lenjanat	3433
4210	Ben-Saman	829
4211	Chadegan	426
4212	Boeen-Daran	1063
4213	Chehel khaneh	152
4214	Damaneh	623
4215	Yancheshmeh	368
4216	Gale shahrokh	1519
4217	Mahyar jonobi	2638

The Zayandeh Rud basin is vulnerable to drought due to significant weather events, desertification, ecological disruption, high population growth rate and overuse of water supplies (Araghinejad, 2011). The important characterisations of the basin will be described below.

3.3.2.1 Geology and topography of the basin

In the Zayandeh Rud Basin the topography between the western part and the eastern part is different. The digital elevation model (DEM) of the study is represented in Figure 3.3 (Esfahan-Iran and 2013). The slopes decrease (from west to east) where the river gets closer to the Gaw Khuny swamp. The western part of the Zayandeh Rud basin is part of the Zagros Mountains and has high elevation and sharp slopes. The upstream of the basin is located in the region. In the Zayandeh Rud river route to the Gaw Khuny swamp, some contributors feed the river, but in recent times, most water from these contributors is already used before getting to the Zayandeh Rud River. Thus, it causes significant water shortage in the basin.

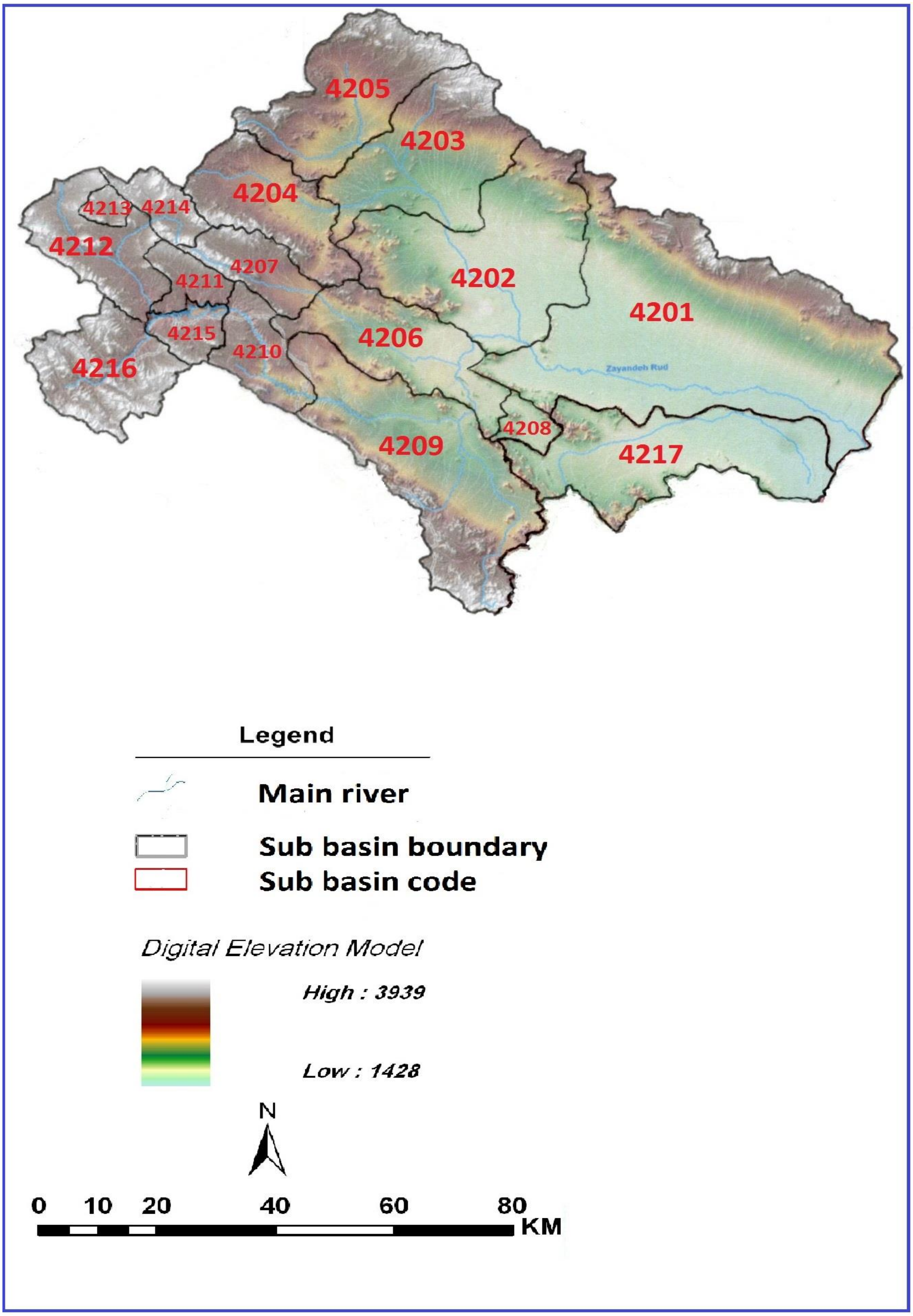


Figure 3.3: Topography of the Zayandeh Rud basin (DEM) (Adapted and modified from The Institution of Meteorological stations network Esfahan-Iran, 2013) (Esfahan-Iran, 2013)

Flows and slopes reduce from west (such as sub-basins 4216, 4215, 4214, 4213, 4212) to east (such as 4201, 4202, 4203, 4206, 4208) by natural drainage losses, evaporation and more recent consumption for irrigation, urban and domestic uses. The river dries out in the Gavkhouni swamp finally, a big white salt playa that forms the bottom end of the basin, lying at an altitude of over 1466m. The flows that reach the playa are now very low. The periods with no water flows in the tail reach of the river have extended. Soils are deeper downstream and are covered with loam and clay loams, which is ideal for the culture of irrigated agriculture.

3.3.2.2 Land use

Generally, pastures and uncultivated lands are common land use in the basin. However, agriculture and irrigated areas cover more than 60% of land use, as shown in Figure 3.4. The major irrigation networks are located in sub-basins 4202, 4203, 4204, 4205, 4206, 4207, 4208 and 4217 which directly get water from the Zayandeh Rud River. These sub-basins are crucial in terms of economic activities of the Zayandeh Rud basin((ERWA), 2011). Small forests (about 9%) areas are located in upstream of the basin, especially in sub-basin 4212, 4213 and 4216.

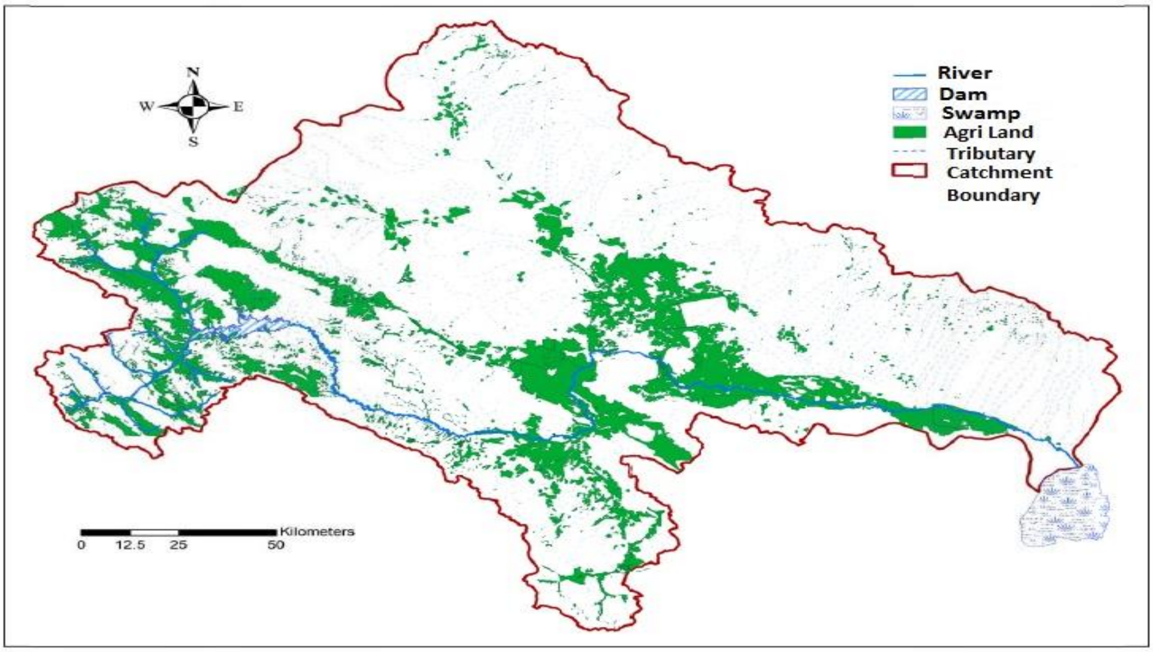


Figure 3.4: Agricultural land use of the Zayandeh Rud basin (Adapted and modified from The Institution of Agricultural Management Esfahan-Iran, 2013) ((MAI), 2013)

3.3.2.3 Climatic features

Based on the Dumarten climate classification method (based on minimum and maximum temperature) most of the basin is a semi-dry to ultra-dry climate and only a small part of the upstream area has a colder climate (Droogers, 2004). Precipitation of the basin is influenced by the Mediterranean rainfall systems which come from the north-west. Significant rainfall occurs in the western mountains. From the west to the east side of the basin rainfall decreases. Annual precipitation ranges from 407.64mm on the upper area of the basin (mostly in the west) to 154.95mm in the centre. The rainfall decreases to 105.42 mm on the Gaw khoni swamp (located downstream).

Temperatures also change in different elevations. The temperature range is from 6 ^{o}C over the west and north west mountains to 15 ^{o}C on the Gawkhoni swamp. In this study, evaporation is estimated by Class A pan. The highest evaporation (2800mm) happens in the Gawkhoni swamp and the lowest (1450mm) is upstream in the western and northern parts.

Evapotranspiration ranges from 1200mm to 2800mm are determined through the Thornthwaite equation (Ahmadi and Fooladmand, 2008). The highest relative humidity 63.3% occurs in winter. However, the lowest is 23.6% in summer. Minimum and maximum annual cloudiness per Octa scale are 1.7 in Gaw Khuny swamp and 2.5 in upper catchment. The lowest wind speed is in November (6.1 ms^{-1}) and the highest occurs in March (9.6 ms^{-1}).

3.3.2.4 Water resources

Most of the surface runoff generates from the higher rainfall in mountainous parts of the basin. The mean annual surface runoff in the basin is about 900 MCM. This is increased by a net import of water (trans-basin diversions by two tunnels) into the basin of 850 MCM to 1487MCM which supplies major agricultural irrigation areas and industries downstream.

3.3.2.5 Water user and trend of the demand

Only water abstraction is estimated because of a lack of information about the efficiency of water works' administration (e.g. leaks in water services; and unauthorised use of water) and uncertainty in the demand metering method. However, there has to be a set of assumptions about return flows into the river from different water users. Return flow specifies the fraction of demand site outflow by: demand site return flow=inflow * (1-consumption). Data sources are Esfahan Regional Water Authority, Ministry of Energy in Iran and Ministry of Agriculture in Esfahan.

3.3.2.6 Institutional arrangement

Currently, the key institution for water supplies management in Iran is established in the Ministry of Energy, and the important sections (or members) are as below:

- Deputy Minister for water associations (Iran Water Resources Management Company)
- Regional water authorities
- Provincial Water and Wastewater Engineering Consulting Companies
- Provincial Miniseries of Agriculture

For the Zayandeh Rud basin, Esfahan Regional Water Authority (ERWA) supervised by the Iran's Ministry of Energy has an important role in making decisions for water resources' exploitation and distribution in the basin. However, two main consultants (e.g. Esfahan Ministry of Agriculture and Esfahan Water Engineering Consulting Company) help the ERWA to get a wider support for water management and water distribution.

Esfahan Environment Authority is responsible for controlling the environmental issues in the Zayandeh Rud basin. The Iranian Environment Organization is an independent organization which is under the supervision of the Iranian president.

3.4 Data types and sources

To determine the historical drought trend, the characterisation and link the drought to water resources and water demands, a statistical calculation and water management model can be used for estimating drought characterisation, impacts and mitigate the impactson water resources and water demands. Before this however, it is necessary to ensure that the data requirements are met at appropriate spatial and temporal resolutions. Three types of data are involved: (1) meteorological data such as rainfall, temperatures, evapotranspiration; (2) hydrological, such as flow measured, water supply, land use and water demands; and (3) socioeconomic related to drought conditions and water demands, such as population and income from crop production.

In this study, three categories of data for the Zayandeh Rud basin were obtained from several sources to address the specific objectives outlined for the research.

3.4.1 Climate data

Two types of meteorological data were obtained: (1) station data and (2) climate projections.

a. Station data

These are observational data from weather stations across the region; the study uses these data to prevent the issue of interpolation and uncertainties in modelled data.

Climatic variables which are used in this study are recorded in 17 stations; among them there are both climatological and simple rain gauges stations. Also the meteorological stations and the hydrological stations are co-located in the basin. The period used in this study is 34years (1971to 2005). For more information about the stations see in appendixII.

Quality control of data is necessary and is used for: (1) detection of gaps in the data (2) detection of physically impossible values. Quality control was carried out for some variables, especially for rainfall and temperature. As the raw data available was complete, only a few values were added or removed to affect the overall quality. Less than 2% of the data was affected by this process. Corrections were made using information from months before or after the problematic value by a linear interpolation method (Fung, 2006). These climate data are applied for evaluating the meteorological drought characteristics in Chapter 4 and as input for the water management model in Chapter 5 and to validate historical climatic data from the climate model in Chapter 6.

b. Climate projections

To evaluate the impact of anthropogenic climate change on the future risk of drought, future climate simulations from the most recent GCMs that cooperated with the Coupled Model Intercomparison Project Phase 5(CMIP5) were downloaded. The data is available for download at the Koninklijk Nederlands Meteorologisch Instituut (KNMI) climate explore gateway at https://climexp.knmi.nl/.

CMIP5 particularly makes a multi-model context for: 1) measuring the mechanisms responsible for model variances in poorly understood feedbacks related to the carbon cycle and with clouds; 2) analysing climate predictability and investigating the capability of models to forecast climate on decadal time scales. The details of the CMIP5 framework are explained in (Taylor et al., 2012). The CMIP5 project has developed simulations compared with the earlier phase (i.e. the resolution in CMIP5 model is finer and has more sets of output fields). The spatial resolution of the atmosphere and ocean components ranges from 0.5 to 4 degrees and 0.2 to 2 degrees. This study applied a wide range of simulations from several climate modelling centres and selected one model from each centre (totally 38 models). The future projections are obtained by the values of their Representative Concentration Pathways (RCPs). In this study, the severest scenario (RCP8.5) is applied to exhibit the severest condition of possible drought events for 2006-2100; RCP8.5 relates to the pathway with the highest greenhouse gas emissions.

Simulations were statistically downscaled to the respective locations before applying them in the study.

3.4.2 Hydrological data

Most of the hydrometric stations were located at the outlet of each sub-basin. Hydrometric measurements of water level surface elevation and volumetric discharge (flow) are taken in the stations. Flumes, limnograph, weirs, etc. are equipment commonly used in the stations.

The most important hydrologic data is river flow in the catchment, which is explained below.

3.4.2.1 River flow in the catchment

1-1) Measured flow

-Stream flow generally decreases from upstream to downstream of the Zayandeh Rud river basin.

- The historical stream flow records (1971-2005) show that there is high seasonal variability.

To indicate these characteristics flow time-series have been plotted for 17 gauging stations located on the Zayandeh Rud basin (Figure 4.2 in Chapter 4).

1-2) Naturalised flow

Natural stream flow is unaffected by consumptive use or reservoir storage. The data are obtained from ERWA. ERWA applied the Thornthwaite water balance model (Thornthwaite, 1948; Mather, 1978; 1979) to creat naturalized flow. The model uses an accounting procedure to analyze the allocation of water among various components of the hydrologic system. Inputs to the model are monthly temperature and precipitation. Outputs include monthly potential and actual evapotranspiration, soil moisture storage, snow storage, and streamflow. The model is obtained from water balance equation in Excel file for the Zayandeh Rud basin. Only three different gauging stations in the Zayandeh Rud basin for 1971-2005 were used for naturalized flow. It shows the flows that would have generated if no development had taken place in the basin. Naturalised flow records were used for calibration in the WEAP model. The values of naturalised flow were compared with the values of the flow which is affected by human activities, to determine the impact of non-climatic parameters on stream flow deficit in the Zayandeh Rud river basin.

3.4.3 Socioeconomic data

To estimate the impacts of drought with and without adaptation plans on water demands, especially for the agricultural water user, the research needs socio-economic data. Some socio-economic data such as demographic data were distinguished from the Iran National Bureau Statistics and the National Population Commission respectively. Data collected included some of the population having access to water and the population growth rate. Some other socio-economic data included all water demands and crop productions and farmer incomes from the production.. All data are available on an annual basis. For the water demands, monthly variations are available. The data are used in analysing the spatial and time characteristics of the water management in two different scenarios (normal condition and dry condition) which are defined in the water allocation and management model of WEAP.

Table 3.2: indicates the summary of the required data, the sources and the specific variables selected for each data type.

Table 3.2: Data sources for the development of the study

Data type	Source	Variables/Description
Meteorological data		
Present climate	The Institution of Meteorological stations networks Esfahan-Iran	Location of meteorological stations, Monthly precipitation. Monthly average temperature, Monthly Evaporation, Monthly evapotranspiration from 1971 to 2005
Climate change scenario(CMIP5 experiments)	Koninklijk Nederlands Meteorologisch Instituut (KNMI) climate explore(http://climexp.knmi.nl/start.cgi?id=someone@somewhere) Earth System Grid –program for Climate Model Diagnosis and Intercomparison (ESG-PCMDI) (http://cmip-pcmdi.llnl.gov/cmip5/data_portal.html)	Both historical and the future climate data of the scenario of RCP8.5 are available at several temporal scales while spatial resolution ranges from 250km to 50km for two variables; it means monthly precipitation, monthly temperature. For this study resolution of 50km are used for the period of 1971-2100
Hydrological and water planning management data		
Primary meteorological input data	The Institution of Meteorological stations networks Esfahan-Iran	Effective precipitation and ET0
Geographical data	The water engineering company (Moshaver yekom)	Contour lines
Water Supply And Hydrological management	Esfahan Regional Water Authority	Location of hydrometric stations, Streamflow. Demand sites. Diversions. Reservoirs. Flow requirements, Dams under study
Land use	• The Institution of Agricultural management Esfahan-Iran • FAO report	Irrigated land distribution. Crop areas, Crop Coefficient.
Socio-economic data	Iranian National Population Commission	Demographic data, Annual population number at district levels, number of farmers, crop yield and income from the crops

Monthly data for the present climate are necessary to calculate drought characterisation and also as input data for the WEAP model to estimate the deficit in stream flow. Usually a series of 30 years is the time minimum used, the records for these meteorological stations are more than 30 years old. Monthly precipitation, temperature and other climatic data were obtained from the Institution of Meteorological stations network Esfahan-Iran.

To investigate the impact of climate change on future intensity, duration and frequency of meteorological drought, at first future climate data are provided from a CMIP5 climate model. Then to analyse the impacts of climate change on future intensity, duration and frequency of hydrological drought, the availability of water resources a hydrological model is needed, which can be driven with the output from a CMIP5 climate model.

For running a rainfall-runoff model of WEAP, one of the most important climate data is effective precipitation that is the amount of rainfall that is not evapo-transpired and available for infiltration and runoff. More details about estimation of effective precipitation is in section 5.2.2 and Equation 3 and 4 in Appendix.

To better understand the physical characterisation of the basin in the hydrological model, digital elevation models (DEM) are necessary. Contour lines determined from the geographical database of the water engineering company (Moshaver Yekom Company) are applied to make digital elevation models.

All hydrological information (indicated in Table 3.2) are relevant and essential for the adequate characterization of the water allocation and management model where all water requirements for all sites have to be determined on a monthly basis as well as operation rules for reservoirs, flow requirements, streamflow diversions.

Also, for agricultural data, all the kinds of crops need to be specified since each types has different crop coefficients that describe the plant’s response to environmental conditions.

Future assumption population and gross domestic product are based on the trend of historical data. More details of future socio-economic data are provided in Chapter 7.

3.5 Methods used for evaluation of drought characterisation, impacts and adaptation plans

As shown in Figure 3.5, in this study, several individual methods were combined to provide a scheme for integrated water resource management during extreme events.

The connections between the various elements are indicated that allow to evaluation of drought characteristics and determine the deficit in stream flow, and also the impact and response of drought on water resources and water demands.

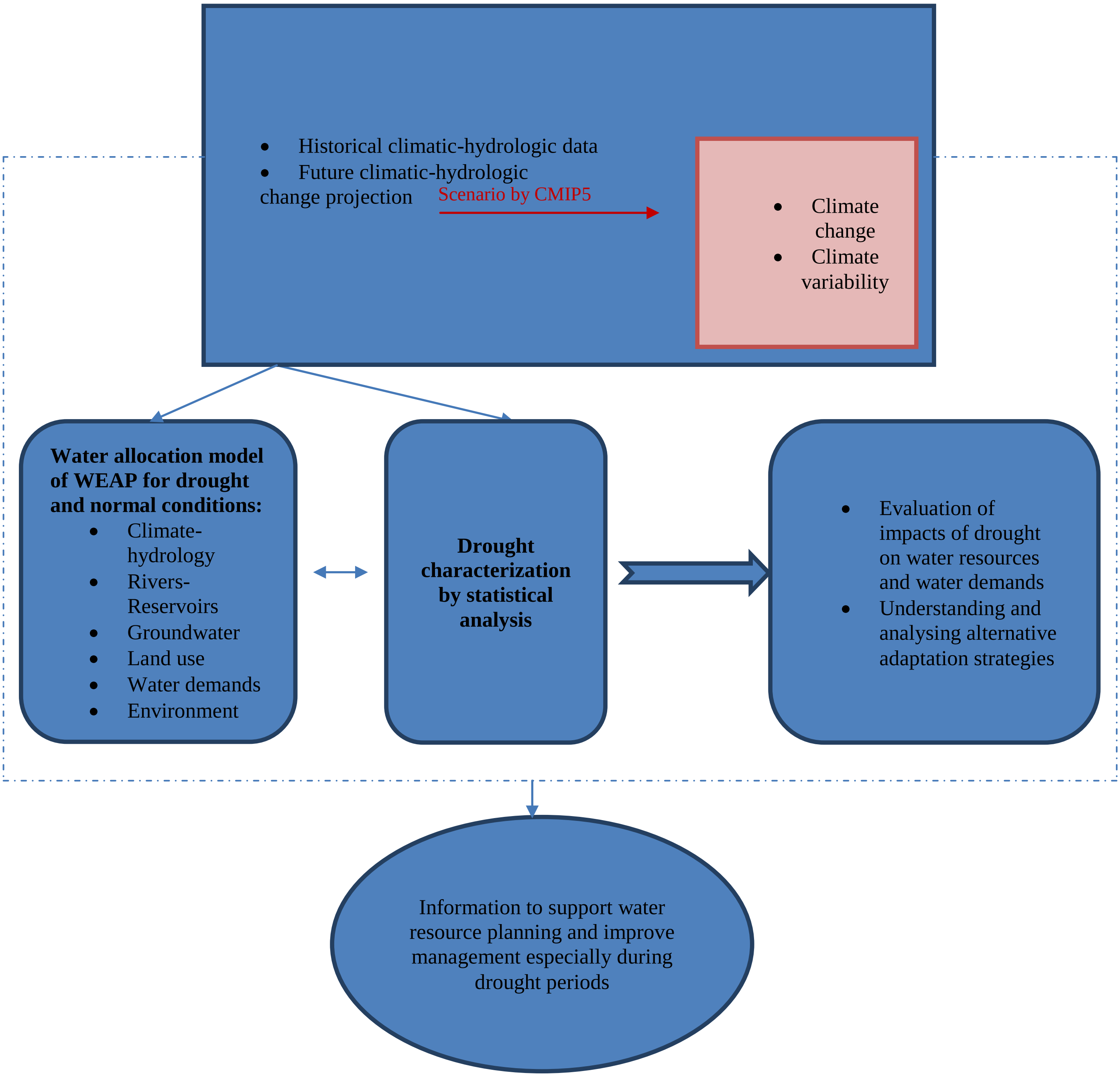


Figure 3.5: A schematic diagram representing the overall approach used in this study to support decision making for use of water resources during drought periods.

To determine the link between climate, drought and impact on water availabilities and water requirements, understanding the natural evaluation of drought processes on a small scale (e.g. region or basin level) is essential.

Depending on different variables and contexts a suitable protocol can be adopted to measure drought and drought impacts(Buurman et al., 2015), the most important being choice of drought indices and associated statistical computatoions as described by(Moneo Laín, 2008). This study uses monthly precipitation and stream flow data for the period from 1971 to 2005.

Statistical analysis was conducted to determine the severity, frequency, period and tendency of drought and distinguish between meterological and hydrological droughts.

McKee et al. (1993) developed the Standardise Precipitation Index (SPI) index and because it has the adaptability for several goals, it is extensively used for drought recognition and calculating (Hayes et al., 1999).

This study uses the (SPI) and also the Standardise Runoff Index (SRI) for the characterisation of meteorological and hydrological drought, respectively. The SPI and SRI are selected because other drought indices are beyond of the scope of this study (see Section 1.2 in Chapter 1) and also because these indices are standardized and the indices can classify droughts with regards to the intensity and duration of each events. For more details about strengths and weaknesses of indices see Table 2.1 and discussion in section 4.4.

SPI identifies rainfall shortages for various timescales, and helps to arrives at potential effects of drought on different types of water bodies (Birgitte von Christierson and 2011). On a lengthier period, precipitation deficit can influence soil moisture, streamflow , reservoir storage and groundwater (Van Loon and Laaha, 2015). Therefore, the standardization allows for comparison of such standardized indices.

Although there are several limitations , the SRI is one of the most proficient methods for recognising hydrological droughts particularly at a small scale (Shukla et al., 2011) as this index combines the effects of hydrological systems impacted upon by anthopogenic uses and climatic data such as, precipitation, temperature. By using SRI, hydrological drought can be characterised at a given location (Liu et al., 2012).

SRI is the "*unit standard normal deviate related to the percentile of hydrologic runoff accumulated over a given duration*" (Shukla and Wood, 2008). SRI estimation includes fitting probability density functions (PDF) to particular frequency distributions of monthly runoffs for a gauge station. The PDF parameters are applied to achieve the cumulative probability of an observed runoff for an identified temporal scale. The cumulative probability is transformed to the standardized normal distribution with mean zero and variance one, which results in the value of the SRI (Wood and Shukla, 2007). Depending on the data sequences, the PDF can be chosen. Based on better fitting of the values, the Gamma distribution has been applied (Naresh Kumar et al., 2009) in the Zayandeh Rud basins.

The SPI and SRI are calculated using monthly precipitation and stream flow, respectively. The total time sequences are fixed to a probability distribution and converted into a normal distribution. So, the values of the SPI and SRI assume to be zero in 'normal' climate-hydrological conditions. However, positive or negative values indicate precipitation above or below the mean.

Duration of the meteorological and hydrological droughts are known by the number of consecutive time intervals for extreme events and frequency of drought is number of extreme drought events for the given duration (such as number of drought per one year). The statistical method is the most common method for investigating drought intensity and drought frequency (Wang et al., 2011a).

Trends/statistical analysis of drought indices

To detect tendencies and temporal alterations in droughts across the study area the Mann-Kendall test is used. The nonparametric Mann- Kendall test is used to the drought time sequence to determine the presence of trends (Mahajan and Dodamani, 2015). Usually, parametric and non-parametric analysis methods are applied to the trend analysis. Linear regression is a parametric method. However, the Mann- Kendall Test is nonparametric methods. The Mann-Kendall test as a non-parametric test for trend finding generated by Mann (1945), and for non-linear examination trend and turning point, the test statistic dissemination was given by Kendall (1975). A non-parametric test is chosen because it can avoid the problem caused by data skew (Mahajan and Dodamani, 2015). Parametric methods are stronger than the non-parametric methods. However, they need data to be independent and normally distributed; while a usually hydrologic variable like rainfall and stream flow is positively or negatively skewed data with some extreme values. Therefore, nonparametric tests are appropriate for rainfall, runoff or streamflow data structures (Ramachandra Rao et al., 2011). The Mann-Kendall test is better than the other statistical step trend tests such as t test and analysis of covariance (parametric techniques) on finding a trend in hydro-meteorological drought time series. The Mann-Kendall test is chosen when different stations are examined in a single study (Mahajan and Dodamani, 2015) (Yue et al., 2002).

WEAP model

The results of the drought characterisation and identified dry years are used as input data in the water allocation model (WEAP model); where the possibility of demand approval can distinguish by considering amount and quality features (Moneo Laín, 2008). This model, measuring some socio-economic impacts of droughts, can evaluate the reliability of the system to deliver water to demand sectors. Also, the model with simulating adaptation scenarios for decreasing drought impacts can raise the level of demand satisfaction to decrease water shortages in climate changes due to decreasing potential precipitation and anthropogenic effects.

The Stockholm Environment Institute (SEI) in 2005 improved the Water Evaluation And Planning (WEAP) model. The WEAP is selected in this study because the system runs on the primitive rule of water equilibrium accounting and is suitable for both municipal and agricultural systems. In this study, WEAP is applied as a water allocation model to simulate water available, which is affected by human abstractions; and to analyse the reliability of the system that can deliver water to the demand sites.

To make a water allocation model by WEAP, at first the model simulates hydrological conditions of the system by using a rainfall-runoff model. The Rainfall Runoff method determines evapotranspiration for irrigated (or rainfed) crops using crop coefficients. The remainder of rainfall not consumed by evapotranspiration is simulated as runoff to a river, or can be proportioned among runoff to a river and flow to groundwater via catchment links.

The hydrology model in WEAP is continuous, beside an investigation region designed as a continuous set of sub-basins that include the full area of the river basin. At every time step, first WEAP simulates the hydrologic variability, which it traverses to each river or groundwater section (Sieber and Purkey, 2011). Then water management is established for the particular time period, where limitations are associated with the features of reservoirs, the network dissemination, environmental policies, and also the preferences allocated to sections of requirments (Moneo Laín, 2008). It uses a “linear programming optimization” procedure that increases the requirment gratification to the biggest expansion possible (Arranz and McCartney, 2007). For more details about the model and algorithm structure see appendix 2(B).

Also more details, technical information and mathematical analysis of the WEAP model regarding the simulation of water resources and water demands can be found in (Yates et al., 2005, Jack Sieber et al., 2005).

Scenarios in WEAP model

Scenario examination is a key point apparatus in WEAP. Scenarios are applied to analyse the model by an extensive sreies of "if" problem, from an adjustment in hydrological variables to alterations in climate, land use, requirement and adjusted strategies influencing the controlling of the structure. Scenarios are different series of hypotheses like climate change, several functioning strategies, expenses and elements that impact on water availability and water demands.

The most significant future scenario will be climate change mixed with human effects. To understand the effect of anthropogenic- climate alteration on the future hazard of water availability and future droughts, future climate simulations from the monthly output data of 38 models are attained from the fifth phase of the Coupled Model Intercomparison Project (CMIP5). The data is available for download at http://climexp.knmi.nl/start.cgi?id. The models have been updated for long term experiments to make a projection of the “forced” responses of climate to changing atmospheric and land cover (Taylor et al., 2011). The CMIP5 project has advanced models contrasted with the prior stages (IPCC, 2013). A bias correction method was applied to downscale the GCM simulations before utilising them to predict possible upcoming drought.

The outputs of the CMIP5 model (precipitation and temperature) are utilised as inputs for the hydrological scheme of the WEAP to estimate future stream flow deficit and calculate future hydrological drought with and without the adaptation strategies. In the context of the adaptations, the more important point is WEAP allows the model user to show dynamic changes in water resources management by programming in model parameters that differ over the course of a simulation. This parameter modification can be established as; 1) external forces upon the model (e.g. as functions of the passage of time) or 2) within the model as a function of the state of the system (e.g. water supply, depth to groundwater, irrigation system, crop pattern and crop yields)(Moneo Laín, 2008).

3.6 Chapter concise

This chapter has discussed the research design of the project. The study area of the thesis, together with the hydrology, predominant climate and anthropogenic factors that affect water deficit in Zayandeh Rud river basin is briefly explained. The data employed in the analyses, models and the generic statistical methods and modelling used for drought characterization, water resource and demand management are also described.

CHAPTER FOUR: DROUGHT CHARACTERISATION, DRIVERS AND TREND ANALYSIS IN ZAYANDEH RUD SUB-BASINS

4.1 Introduction

Droughts are caused by conditions with temporarily subnormal water availability. They appear in various components of the hydrological cycles and in every hydro-climatic region (Wilhite et al., 2000a). All droughts originate from a deviation from normal situations (Tallaksen and Van Lanen, 2004). These aberrations can be in precipitation, soil moisture, streamflow or groundwater. Droughts can be classified into meteorological, soil moisture and hydrological (Hisdal et al., 2001). A deficit of precipitation characterizes meteorological droughts, often incorporated with potential evapotranspiration that is higher than normal, for a long period and over a vast area (Tallaksen and Van Lanen, 2004). Soil moisture droughts originate from a loss in soil moisture, along with high potential evapotranspiration and low precipitation. Hydrological droughts may happen in both streamflow and groundwater. Groundwater droughts can be the result of below average precipitation for long periods. However, streamflow droughts can be generated in shorter periods with no precipitation; since surface runoff could be a larger component of the stream flow (Peters et al., 2003). Extension drought is a process where decreasing in precipitation results in a below normal deduction in soil moisture, stream flow or groundwater (Tallaksen and Van Lanen, 2004). Droughts can happen in all hydroclimatic regions and vary in duration, frequency and severity (Hisdal et al., 2001). For example, semi-arid or arid areas, unlike rivers in humid areas with high discharge, have transitory streams with very low or even no discharge for a long time (Ian Simmers, 2003). Also (Van Lanen, 2007) demonstrates that characterizing droughts can be difficult when using only one indicator. Further research using a vast set of drought indicators on a given regional scale can provide more information. Despite problems in defining droughts in arid regions overall results are encouraging. The effects of different hydro climatic conditions on the severity, frequency and duration of droughts have not been fully understood. The important components of drought monitoring and assessment are drought indices, since they make complex interrelationships between many climate and climate-related parameters easy. Over the years, different indices have been applied to investigate and monitor droughts. The Standardized Precipitation Index (SPI) is one of the best and most commonly used indicators (See section 3.5 in Chapter 3). Stream flow and then, SRI are applied as indicators of hydrological drought. Previous studies indicate that the SPI is an applicable indicator for measuring drought onset. However, the SRI detects drought persistence more accurately. Zayandeh Rud basin is an example of a semi-arid region, where water demand especially for agriculture is very sensitive and vulnerable to extreme droughts. About 100000 hectares of Zayandeh Rud's agricultural lands were influenced by a drought between 1998 and 2001. Due to the correlation between the boost warm pool-La Nina composite and the climate anomalies of 1998-2001, the prolonged La Nina was an important key factor in the central and southwest Asian drought (Barlow et al., 2002). There is some proof that the recent drought in central Asia is associated with the combination of prolonged La Niña circumstances in the eastern and central equatorial Pacific and uncommonly warm water in the western Pacific Ocean.

The probability of dry conditions is high during La Nina events and during warm El Nino-Southern Oscillation (ENSO) phases. The risk of drought in winter in the middle (the Zayandeh Rud basin), south-eastern and north-western parts of Iran is high FAO & GHOLIZADEH, 2015), despite the rest of Iran receiving above average precipitation (Nazemosadat and Ghasemi, 2004). Previous research (Araghinejad et al., 2006, Karamouz and Araghinejad, 2008) has shown there is a significant correlation between El Nino and hydrological droughts in western Iran. Some studies have detected drought in Iran without paying adequate attention to the rainfall and streamflow variability based on non-parametric trend identification. In most of the studies investigation of the spatial and temporal characterization of drought is missing, despite drought occurring more than other natural disasters in number and frequency.

The principal objective of drought condition assessment is the first step for water planning resources to decrease and control the negative influences of future occurrences. Therefore, the objectives of this chapter are:

- To determine the characterisation of meteorological and hydrological drought using different drought indicators of SPI and SRI at the 12-month timescale in 17 rain gauge and hydrometric stations across the Zayandeh Rud basin of Iran. It includes the impact of climate on the performance of the drought indicators.
- To analyse drought characterization changes in time; specifically the upward trends in the drought severity series using the Kendall nonparametric test for 34 years (1971 to 2005).
- To identify the spatial characteristics and temporal trends of the drought indices.
- To quantify the severity, duration and frequency of the drought for each sub-basin.
- To consider causes of historical droughts including large scale climate, basin climate and some examples of human activities which impact water scarcity and drought in the basin.

This chapter is organized into five sections. The study area and data sets with methodology illustration are explained in Section 2. Section 3 and 4 contain results and a discussion on documents and the changes in trends of meteorological and hydrological droughts in the Zayandeh Rud basin and also identify intensity-duration-frequency of droughts between 1971-2005. Moreover, the causes of the droughts such as large scale climate, basin climate and human effects on drought are considered. The last section includes a summary and conclusion.

4.2 Materials and methods

4.2.1 Data

Monthly precipitation and stream flow data from the 17 rain gauge and hydrometric stations from 1971 to 2005 was obtained from the Meteorological Organization of Iran and Esfahan regional water authority. Meteorological and hydrometric stations' positions utilized in this study are indicated in Figures 4.1 and 4.2 and their geographical coordinates are shown in Table 4.1.

Table 4.1: Details of the meteorological and hydrometric stations used in the study

Station	Name of meteorological station	Name of hydrometric station	River	Longitude (E)	Latitude (N)	Elevation (m a.m.s.l.)
1	Gale shahrokh	Ghale shahrokh	Zayandeh rud	50˚27'11"	32˚39'46"	2109
2	Boeen	Boeen-Eskandari	Plasjan	50˚09'34"	33˚04'34"	2449
3	Mirabad	Mirabad-Chehel khane	Khansar-Khoshke rood	50˚14'26"	33˚04'39"	2540
4	Chadegan	Chadegan-Mandarjan	Zayandeh rud-Samandegan	50˚38'10"	32˚45'30"	2120
5	Heydari	Heydari-Yan cheshme	Deraz dare-Zayandeh rud	50˚35'09"	32˚39'33"	2204
6	Damane fereydan	Damane –ghale babamohammad	Rood daran-Khsoke rood	50˚29'55"	33˚00'53"	2388
7	Ghale nazer	Ghale nazer-Khamiran	Morghab	50˚49'22"	32˚52'51"	2209
8	Sad Zayandeh rud	Sad Zayandeh rud	Zayandeh rud	50˚44'49"	32˚43'48"	2173
9	Hamgin	Hamgin	Khoshke rood	51˚28'12"	31˚54'44"	2256
10	Mohammadabad jarghoye	Mahyar jonobi-Hasan abad	Zar cheshme	52˚05'28"	32˚19'09"	1628
11	Varzaneh	Varzaneh	Zayandeh rud	52˚38'49"	32˚25'10"	1495
12	Zofre falavarjan	Zofre falavarjan	Zayandeh rud	51˚29'54"	32˚30'08"	1648
13	Mahyar	Mahyar-pol chom	Zayandeh rud	51˚28'44"	32˚16'20"	1686
14	Khondab	Pol kale-lenjanat	Zayandeh rud	50˚53'26"	33˚08'18"	2010
15	Vazan vazan meyme	Hanjen meyme	Laghzi	51˚11'36"	33˚24'51"	2013
16	Morche khort	Morche khort	Rood Shoor	51˚29'10"	33˚04'34"	1694
17	Esfahan	Esfahan	Zayandeh rud	51˚41'19"	32˚38'10"	1586

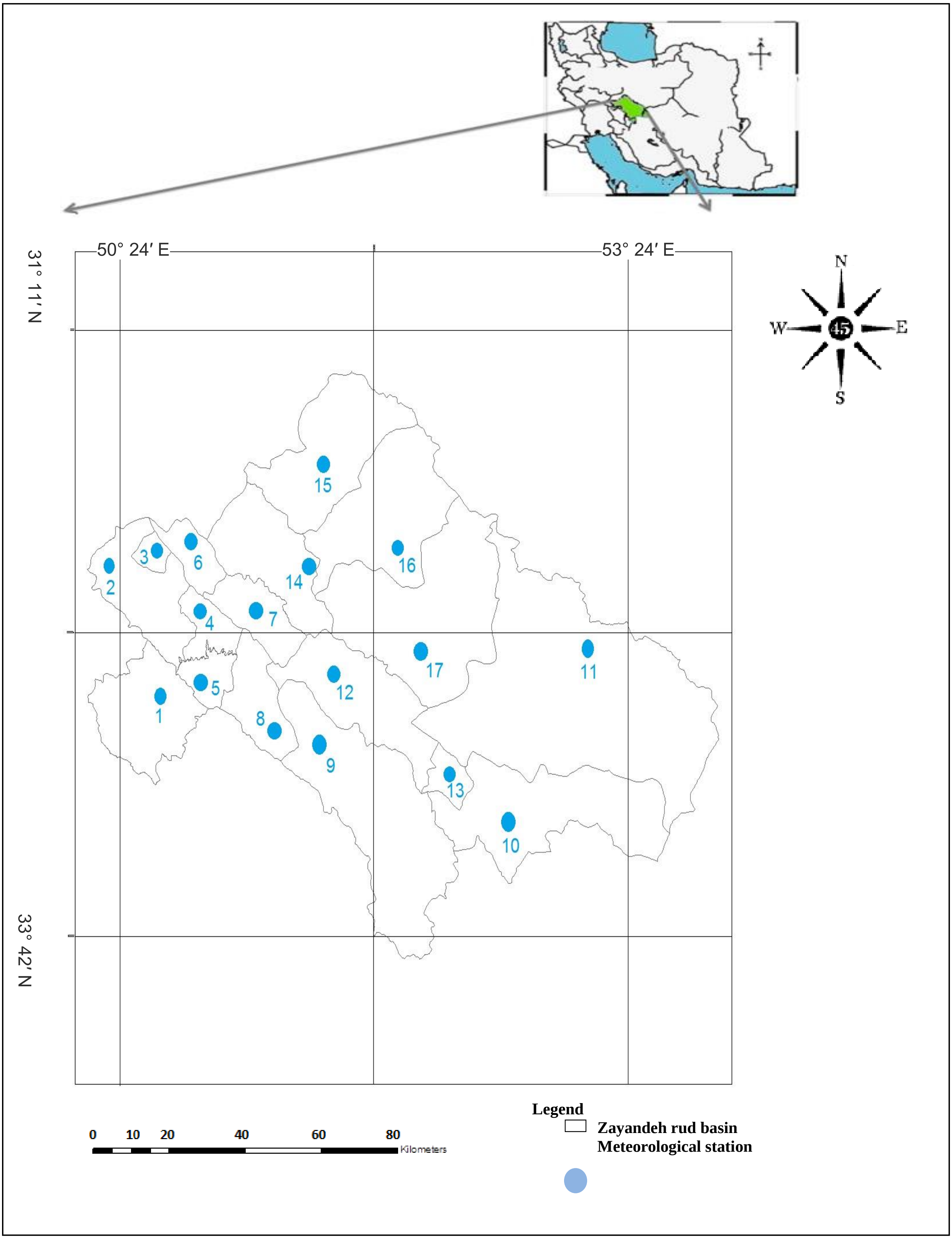


Figure 4.1: Geographical location of the study area and meteorological stations

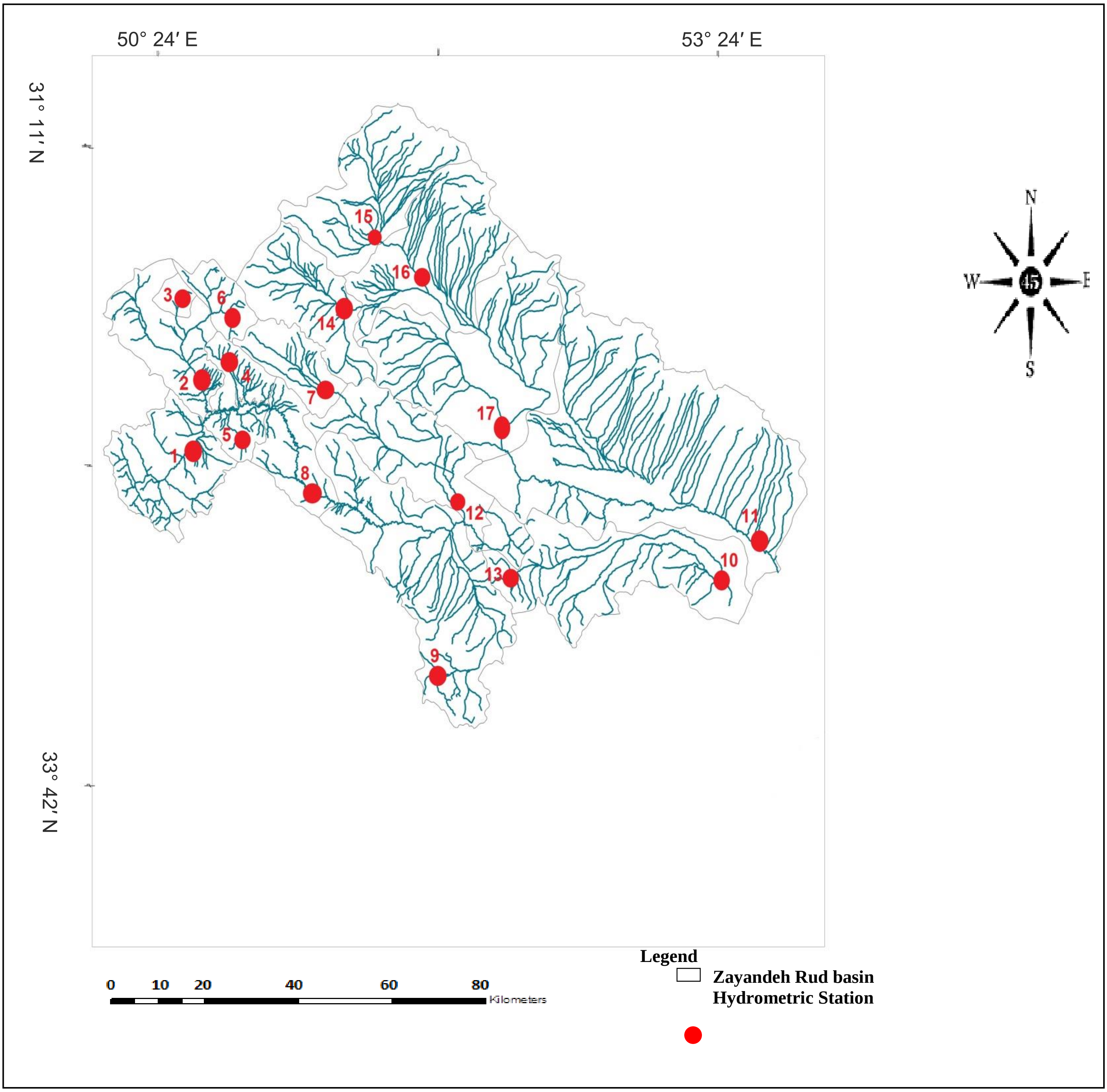


Figure 4.2: Geographical location of the study area and spatial distribution of hydrometric stations

4.2.2 Selected drought indicators

Numerous drought indicators have been developed and validated for various regions of the globe (Wang et al., 2011b). In this section a more detailed description of selected indicators from Chapter 2 is given, including equations to calculate the performance of each indicator and its classification (e.g. duration of droughts, severity of droughts, and distinction of drought categories). The indicators were selected based on their strengths and weaknesses in combination with hydrological expert knowledge (Van Lanen et al., 2013).

We use a multi-index approach for drought assessment. These indices include (1) SPI and (2) SRI as a determination of meteorological and hydrological drought. A 12-month SPI (or SRI) is a comparison of the precipitation (or streamflow) for 12 months (of hydrological year which starts from October and end in September)) with the same 12 months during all the previous years of available data. The SPI and SRI at this time scale reflect long-term precipitation and streamflow patterns.

The chosen drought indices are computed as follows(Golian et al., 2014).

A drought is a multifaceted event, and a single variable (or indicator) is insufficient to reveal the complete characteristics of drought, as they may be affected by numerous variables (e.g. precipitation, runoff, soil moisture)(Golian et al., 2014).

This research is based on some statistical analysis for three important drought characterisations (intensity, duration, and frequency).

The study examines trends and temporal changes in droughts over the sub-basins. The nonparametric Mann-Kendall test is used to the drought time series to investigate the presence of trends (Golian et al., 2014).

4.2.2.1 Meteorological drought indicators

Standard Precipitation Index (SPI)

For examination of the spatial and temporal extents and severity of drought occurrence in the study area, SPI is applied. SPI makes a comparison of the precipitation over a given period with the precipitation totals from the same period in the historical record (Angelidis et al., 2012). Computation of the SPI involves fitting a gamma probability density function to a particular time series of precipitation (McKee, 1993); whose probability density function, g(x), is described as:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad \text{for} \quad x > 0 \qquad \text{(Eq.1)}$$

Where, $\alpha>0$ is a shape parameter, $\beta>0$ is a scale parameter, and $x>0$ is the value of precipitation; $\Gamma(\alpha)$ shows the gamma function, which is expressed as:

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1} e^{-y} dy \qquad \text{(Eq.2)}$$

Table 4.2: Drought category classification by SPI value and corresponding event probability

SPI value	Category	Probability (%)	Approximately number drought time in 100 year	Severity of event
SPI≥2.00	Extremely wet	2.3		
1.5≤SPI≤1.99	Severely wet	4.4		
1.00≤SPI≤1.49	Moderately wet	9.2		
0.99≤SPI≤0	Mild wet	34.1		
0≤SPI≤-0.99	Mild dry	34.1	33	1 in 3 year
-1.00≤SPI≤-1.49	Moderately dry	9.2	10	1 in 10 year
-1.5≤SPI≤-1.99	Severely dry	4.4	5	1 in 20 year
SPI≤-2.00	Extremely dry	2.3	2.5	1 in 50 year

Fitting the distribution to the data needs α and β to be determined as follows:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right), \text{ with } A = \ln(\overline{x}) - \frac{\Sigma \ln(x)}{n} \text{ and } \beta = \frac{\overline{x}}{\alpha} \qquad \text{(Eq.3)}$$

In the equation, the number of observations is indicated by n. This allows the rainfall distribution at the station to be shown efficiently by a mathematical cumulative probability function as given by:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta} dx \qquad \text{(Eq.4)}$$

It is possible to have various zero values. To measure the probability of zero value, because the gamma distribution is unknown for x=0, the cumulative probability function for gamma distribution is changed as:

$$H(x) = q + (1 - q)G(x) \qquad \text{(Eq.5)}$$

Where q shows the probability of zero precipitation. Therefore, the cumulative probability distribution shift into the standard normal distribution to yield the SPI by fitting the log-normal distribution with the sample mean and variance of the logarithmic shifted data μ_y and σ_y, the SPI becomes:

$$SPI = Z = \frac{\ln(x) - \mu_y}{\sigma_y} \qquad \text{(Eq.6)}$$

"Since the gamma distribution likely towards the normal as the shape parameter α likely to infinity, it is possible to use the normal probability distribution instead of gamma, which is computationally easier to estimate and maybe more accurate, due to a better matching to the data. In this case, the SPI index can calculate simply" (Mansouri Daneshvar et al., 2013):

$$SPI = Z = \frac{(x - \mu)}{\sigma} \quad \text{(Eq.7)}$$

Where, μ and σ are the case calculation of the mean precipitation and standard deviation.

Table 4.2 represents the drought category classification for the SPI as standard values. Positive SPI values show bigger than median precipitation, and negative values are smaller. As the SPI is normalized, drier and wetter climates can show in an equal way.

The threshold level for drought identification was set to zero following previous studies about drought identification in Iran. Also the Z score where at the threshold below zero with q_{20} (20% is not the exceeded frequency) the standard deviation is below the mean (Tallaksen and Stahl, 2014) and indicates drought.

For a given value of precipitation, the cumulative probability for the gamma distribution is transformed to a standard normal distribution. Then the SPI value is the Z-value in the standard normal distribution corresponding to the cumulative probability [Mc Kee et al., 1993]. The transform ensures that all distributions have a common basis. The detailed information used to assess SPI can be found in (McKee, 1993).

4.2.2.2 Hydrological drought

Standardized runoff index (SRI)

The standardized runoff index proposed by Shukla and Wood is used to show hydrological drought; it is computed using a procedure similar to the SPI. To compute SRI, a time series of monthly streamflow volumes need to be available (hydrologic stations in Table 4.1).

Positive SRI values represent wet conditions; meanwhile negative values show a hydrological drought. Based on the SRI, five conditions of hydrological drought are designated by an integer number ranging from 0 (non-drought) to 4 (extreme drought). The statuses of hydrological drought can be calculated by the standards of Table 4.3.

Table 4.3: Drought category classification by SRI value and corresponding event probability

State	Description	Criterion	Probability (%)
0	Non-dry	SRI≤0.0	50.0
1	Mild dry	-1.0≥ SRI<0.0	34.1
2	Moderate dry	-1.5≥ SRI<-1.0	9.2
3	Severe dry	-2≥ SRI<-1.5	4.4
4	Extreme dry	SRI<-2	2.3

4.2.3 Statistical analysis

4.2.3.1 Drought trend

To detect trends and temporal changes in droughts over the study area the Mann-Kendall test is used. (Mann, 1945) improved this test originally and later (Kendall, 1948) derived the test statistics distribution. The null hypothesis H(0) represents no significant trend in the examined time series. If the *P*-value of the test is less than the significant value (e.g., 0.05 indicating a 95% confidence level), this hypothesis is rejected. This test could explain good performance for trend detection in hydrology and has been used in drought studies (e.g. (Damberg and AghaKouchak) (Golian et al., 2014).

The Mann-Kendall test does not consider the magnitude of the values; however, it depends on the rank of values in historical observations. In this test, each value x_1 x_n from a time series of n values is compared with all other values. For a positive difference between the data points, the so-called S statistic is raised by +1, it is declined by -1 for a negative difference. The S statistics remain constant for zero differences (Eq. 8 and 9):

$$s = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j x_i), \qquad (8)$$

Where,

$$sgn(x_j - x_i) \begin{cases} +1, (x_j - x_i) > 0 \\ 0, (x_j - x_i) = 0 \\ -1, (x_j - x_i) < 0 \end{cases} \qquad (9)$$

Therefore, a large positive value of S shows a significantly rising trend, and a large negative value, a dramatically decreasing trend. The nonparametric assumption of Mann-Kendall's test, using a time series with a large number of values, allows the use of a regular Z test to estimate whether a trend is strong (Yue et al., 2002, Golian et al., 2014).

$$z = \begin{cases} \dfrac{S-1}{\sqrt{\dfrac{n(n-1)(2n+5)-\sum_{j=1}^{q} t_{j(}t_{j-1)(2t_j+5)}}{18}}}, & if\ S > 0 \\ 0, & if\ S = 0 \\ \dfrac{S+1}{\sqrt{\dfrac{n(n-1)(2n+5)-\sum_{j=1}^{q} t_{j(}t_{j-1)(2t_j+5)}}{18}}}, & if\ S < 0 \end{cases}$$

Where n is the sample size; q represents the number of zero difference groups in the data set; and t_j shows the number of data points in the jth zero-difference group. In this study, a *p*-value of 0.05 (confidence level of 95%) is applied as the criterion of statistical important of a trend. The Mann-Kendall test returns an H value of 1 if a statistically significant trend identified (i.e., the null hypothesis of no trend is rejected). Therefore, the test returns an H value of 0 if the null hypothesis of no trend cannot reject at a significant level of p=0.05 (AghaKouchak A, 2013, Golian et al., 2014).

4.2.3.2 Severity-period-frequency of drought

Drought features consist of beginning, finish off, severity, frequency, duration and, areal extent (Andreadis and Lettenmaier, 2006). For any drought indicator, these drought characteristics could quantify. In this study, "intensity, duration and frequency (IDF)" of drought (calculated by SPI and SRI) is deliberated. The IDF quantities are particular to the study area, however, they create explanation of drought features alteration under the given time periods(Wang et al., 2011b). For determining the drought IDF, some measures are applied in this study:

1. Define the temporal dimension for calculating the drought indices. The available data are 34 years' monthly time series of precipitation and stream flow. The monthly values of these variables are applied to relate to drought indices.

2. Define the drought occurances. SPI and SRI quantities among 0 and -0.99, -1.00 and -1.49, -1.50 and -1.99, and less than -2.00 are known as slight drought, medium, severe, and intense drought, correspondingly Z score and previous study in Iran(Asefjah et al., 2014). Drought happenings with a severity fewer than zero are shown.
3. Build the intensity-duration-frequency of drought and do some statistical analysis (by SPSS software) for drought trend for the period of (1971-2005).

4.2.4 Analysis of experimental data to understand cause of the recognized drought

To understand better causes of the drought during the dry years in the basin, some related experimental data from different institutions are collected. The relationship between the data and their impact, estimated by SPI and SRI are analysed. In this study three main factors (large scale climate, the basin climate and human activities) that cause drought in the basin are obtained and the experimental data used and related with drought characterisation are listed below:

1) Monthly average SOI and NAO per year

2) Annual average evapotranspiration

3) Annual average yield by developed water resources in the basin

4) Average annual irrigation water requirement and annual irrigated area

5) Average irrigation efficiency

6) Cropping pattern changes

7) Average of urban population and urban water requirements per year

Table 4.4 indicates the summary of the required data, the sources and the descriptions for each data type. More details about the data and the related analysis are in section 4.3.7.

Table 4.4: Data sources for the development of the causes of drought in the Zayandeh rud basin

Data type	Source	Time period	Description
Monthly average SOI and NAO index	Climate Prediction Center (http://www.cpc.ncep.noaa.gov/)	Monthly data for 1971-2006	During dry period in dry years, SOI reduced and NAO increased (low SOI and high NAO are accompined by reduced rainfall and streamflow)
Anuual average evapotranspiration	Temperature data come from the Esfahan Regional Meteorology Agency. Then for this study evapotranspiration is calculated by Thornthwaite equation.	Annual data for 1971-2006	During dry periods, evapotranspiration is higher than rainfall
Annual average yield by developed water resources in the basin, annual streamflow and annual water demands	Esfahan Regional Water Authority	Annual data for 1971-2006	The construction of new water resource developments caused over water consumtions, however streamflow in downstream decreased significantly. So during dry years it effects on hydrological drought
Annual average irrigation water requirement and annual irrigation area	The data come from Ministry of agriculture in Iran (Jahad keshavarzi) and the ministry estimated irrigated area by satellite images.	Annual data for 1988-2006	From 1988 to 2006 the irrigated area in all sub-basins increased, especially in recent dry years. So, it can increase the vulnerability to hydrological drought because of reducing the flow of water by increasing drainage.

Table 4.4: Continued

Average irrigation efficiency	The data come from Ministry of agriculture in Iran (Jahad keshavarzi). Irrigation efficiency calculated by the equation in appendix	Annual average data for 1971-2006	Water use efficiencies of all irrigation system is very low (34%). So, during dry periods, because of high water losses and more water demands it aggravated hydrological drought
Crop pattern change	The data come from Ministry of agriculture in Iran (Jahad keshavarzi) and the ministry estimated crop pattern change by satellite images.	Average for the priod of 1965-2000	Applying 20% conversion from wheat to rice cropping from 1965 to 2000 caused increase in water consumtion and higher risk of hydrological drought
Average of urban population and urban water requirement per year	Census data from Statistical Center of Iran	Annual average data for 1956-2016	A increase rate of 5.9% in population per year happened from 1956 to 2006. So domestic and industrial demands increased significantly which aggravated hydrological drought

4.3 Results

Precipitation variability, which is the most important key for both meteorological and hydrological drought is analyzed for 1971 to 2005. Then, drought threshold indicators (e.g. SPI and SRI) are examined and significant upward trends of the indicators are evaluated for the period. Next, drought characteristics in terms of intensity, duration and frequency are examined and compared for each dry year. Finally, the causes of the droughts which are divided into three main drivers (large scale climate, the basin climate and human influences) are measured.

4.3.1 Precipitation variability

4.3.1.1 Inter-annual variation of rainfall

In the Zayandeh Rud river basin, precipitation often occurs over a short time, and the annual rainfall has varied during the past decades. The main cause of this annual rainfall variability is the changing position of synoptic systems and variation in the number of cyclones passing through (Modarres and de Paulo Rodrigues da Silva, 2007). The analysis and characterization of drought periods in a river basin must be preceded by a description of the variability of precipitation. The average values, standard deviation and variability coefficients are summarized in Table 4.4. The average precipitations are higher in the stations in the upper sections of the Zayandeh Rud River or their main tributaries. In the basin, in the mountainous area on the upstream (especially in The North-West side) the average river precipitation is higher in the sub-basins 4216, 4213, 4210, 4215, 4212. This can be attributed to the orographic rainfall in the regions. There is also a slight trend of variability coefficients of average precipitation values from the top to the end of the river; this trend is more significant when analysing monthly precipitations. The coefficient of variation (CV) increased with decreasing rainfall. So for example, in sub-catchment 4216 in upstream, CV is 29%, but in sub-catchment 4201 in downstream with lower precipitation, the CV is 35%. However, the total annual precipitation in the basin is low. Figure 4.3 shows the box plots of annual precipitation for 34 years (1971-2005) for the sub-catchments attained from the meteorological stations of the basin. Generally the most significant low precipitation is in sub-catchments 4201, 4202, 4203, 4204, 4204, 4205, 4206, 4207, 4208, 4209 and 4217. Only in sub-catchments 4211, 4212, 4213, 4214, 4215 and 4216, which are located in the north and west part of the Zayandeh Rud, is the precipitation higher than the rest of the basin. Therefore, the high rainfall in those sub-catchments contributes to more runoff. The spatial pattern of the rainfall is mapped in Figure 4.5.

Table 4.5: Variability of annual precipitation in the Zayandeh Rud sub- basins

Sub-catchment	Average (mm)	Std.Dev (mm)	Var.Coef (%)
4201	124.76	43.80	35
4202	121.06	42.48	35
4203	128.96	48.88	37
4204	164.6	44.69	27
4205	180.82	67.36	37
4206	154.95	73.62	47
4207	183.04	51.99	30
4208	147.55	37.85	26
4209	119.92	37.22	32
4210	365.0	84.48	23
4211	248.85	77.81	30
4212	380.30	101.00	25
4213	380.00	101.00	25
4214	379.24	103.37	26
4215	244.99	75.07	29
4216	407.64	122.69	29
4217	105.42	32.59	31

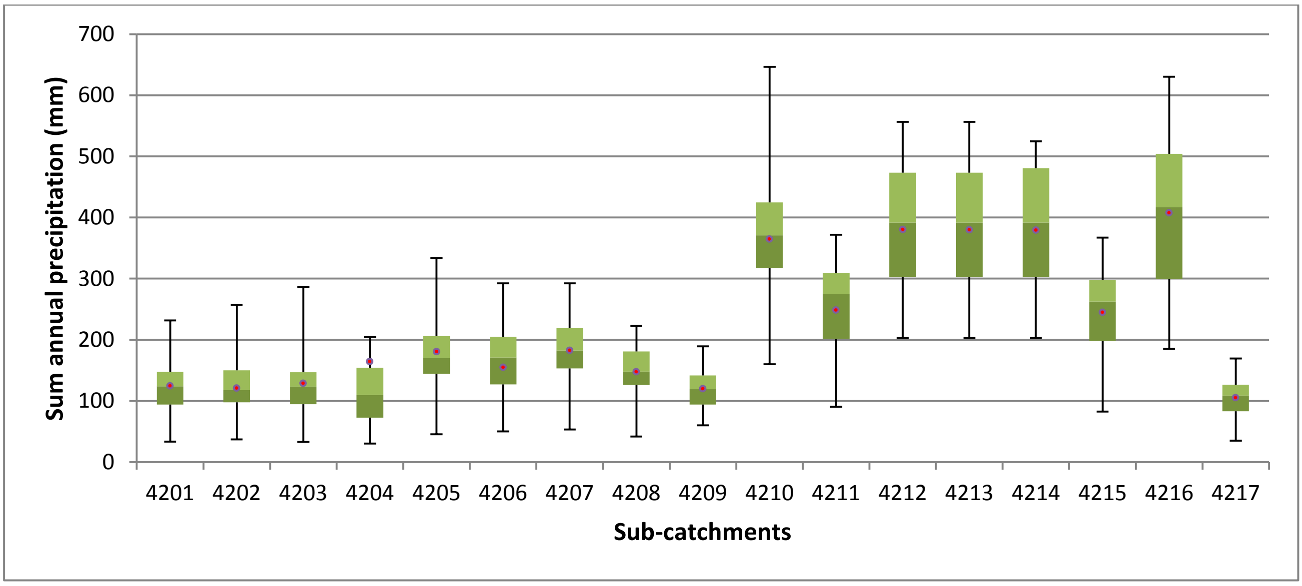


Figure 4.3: The box plots of Sum annual precipitation during the year of 1971 to 2005. In each box, the central points are the mean value, the central mark (horizontal line) is the median, the lower and upper edges of the box are the 25th and 75th percentiles, respectively, and the whiskers extend to the min and max data points.

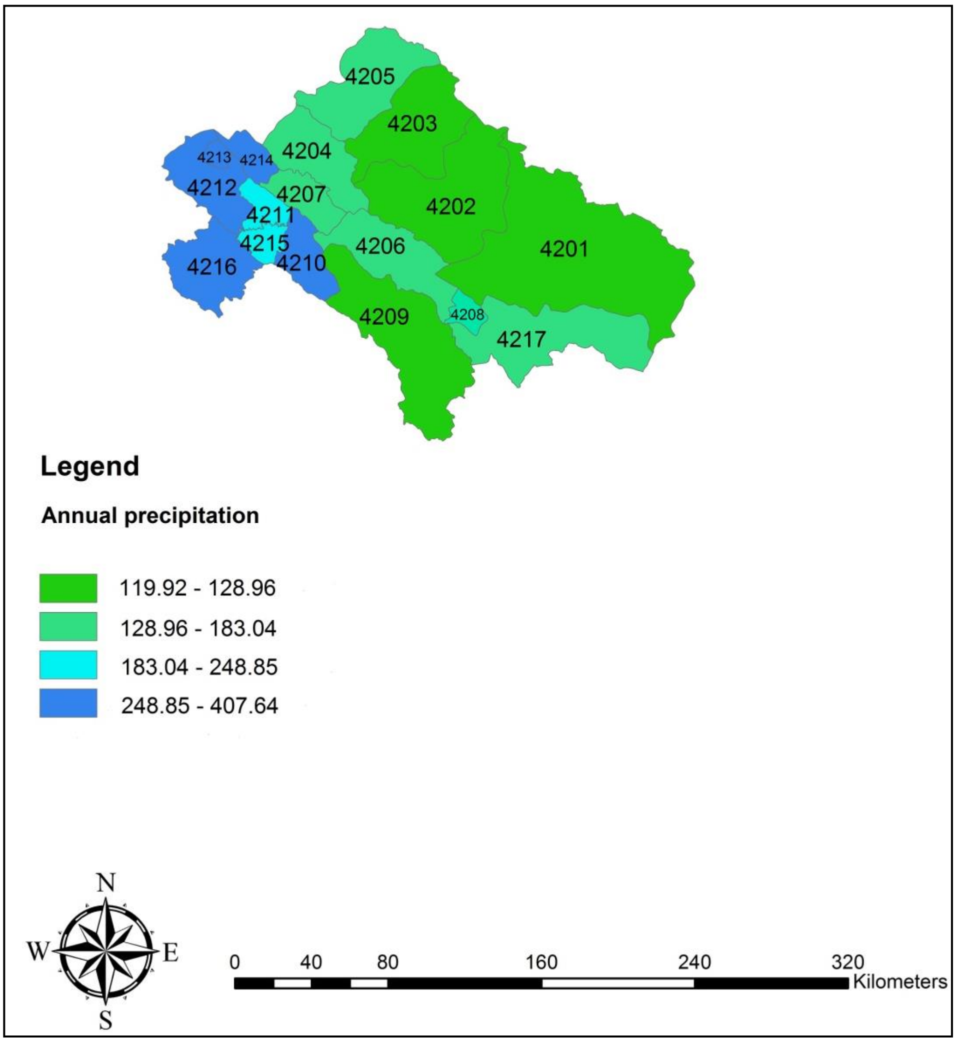


Figure 4.4: Spatial patterns of the mean annual precipitation (mm)

4.3.1.2 Intra-annual variation of precipitation

The intra-annual variation of precipitation was measured by applying the monthly median values of precipitation computed at all stations. The result is shown in Figure 4.5. The basin mean of 308 mm for 1971-2005 was computed using station data.

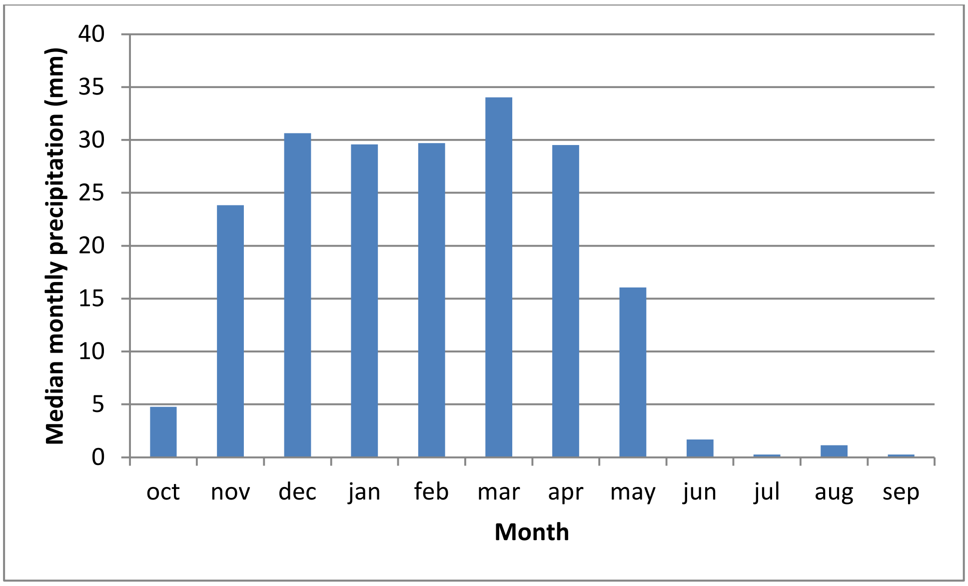


Figure 4.5: Median monthly precipitation (mm) for 1971-2005

The monthly values represent the seasonality of rainfall. The wettest and driest months in the basin are March and July respectively; with the wet season spanning December to April and the dry season being June to September.

4.3.2 Drought threshold indicators

By the indices explained, drought episodes have been evaluated. We can identify meteorological drought as in previous scientific studies on drought (Wilhite et al., 2005, Moneo Laín, 2008), with using the Standardized Precipitation Index (SPI) for the historical sequences of monthly precipitation. Then in order to examine the shortfall durations from the hydrological perspective(Moneo Laín, 2008); the SRI is used to represent hydrological drought episodes. These two different droughts have various expansion durations, response and effects. Meteorological drought handles crop yield losses, particularly in rain-fed crops; because irrigated crops rely on standardized organisations, which prevent the effect of small precipitation duration. The organisation should consume stocked water therefore, the continuous drought does not decline the quantity of the system or the standard level (Wilhite et al., 2000a, Moneo Laín, 2008) (Garrote et al., 2007).

4.3.2.1 Standardized precipitation index (SPI) and standardized stream flow volume (SRI)

For drought recognition, the threshold level was fixed to zero resulting the outcomes of earlier studies in Iran and also the Z-score, which was explained in the methodology (Paulo et al., 2003). Therefore, if the SPI and SRI quantities are lower than zero and q20 threshold (i.e. 20% non-exceedance frequency) for a given month this shows drought conditions. This threshold indicates the changing of standard deviations that the rainfall or stream flow would deviate from the long-term mean. In the Zayandeh Rud basin, the upper stations display fewer coinciding drought episodes among the rest of the basin.

Figures 4.6, 4.7 and 4.8 show the results of the SPI and SRI for every meteorological and hydrometric station in the period 1971-2003. The wet and dry episodes can be understood simply from the figure, because of the small responsiveness to the SPI 12 to the low precipitation that occurs in the semiarid and arid areas.

The majority of the drought events for October-September identified in the years of 1972-1973, 1976-1977, 1980-1981, 1984-1985, 1990-1991, 1996-1997, 1998-1999, 1999-2000 and 2000-2001. All stations experienced drought similarity at least for one month for the reference period. All of the rivers of the study region faced at least one severe drought during the last decades especially in the year 2000-2001. The most significant meteorological and hydrological drought can be identified at sub-basins 4201, 4203, 4204, 4206, 4207 and 4208. In general, the meteorological and hydrological years of 1972-1973, 1976-1977, 1980-1981, 1984-1985, 1990-1991, 1996-1997, 1998-1999, 1999-2000 and 2000-2001 showed the driest years. The most recent severe stream flow drought for all sub-catchments happened in the hydrological years of 1998-1999, 1999-2000 and 2000-2001.

Over half of the population in the Zayandeh Rud basin has been influenced by extended droughts in 1998-2001 (Raziei at al. 2009). The drought in 1999 was the most significant to water resources and agriculture of the basin. Drought causes a high immigration of people from rural to urban areas (Yazdani and Haghsheno, 2008). The United Nations measures the loss of agriculture and livestock at $2.5 billion in 2001, up from $1.7 billion in 2000. After three years of drought between 1998 and 2001, which the United Nations mentioned as the most significant in Iran for 30 years, many parts of the Iran wetlands such as Gavkhooni wetland in Zayandeh Rud basin became drier, and many farmers struggled to survive.

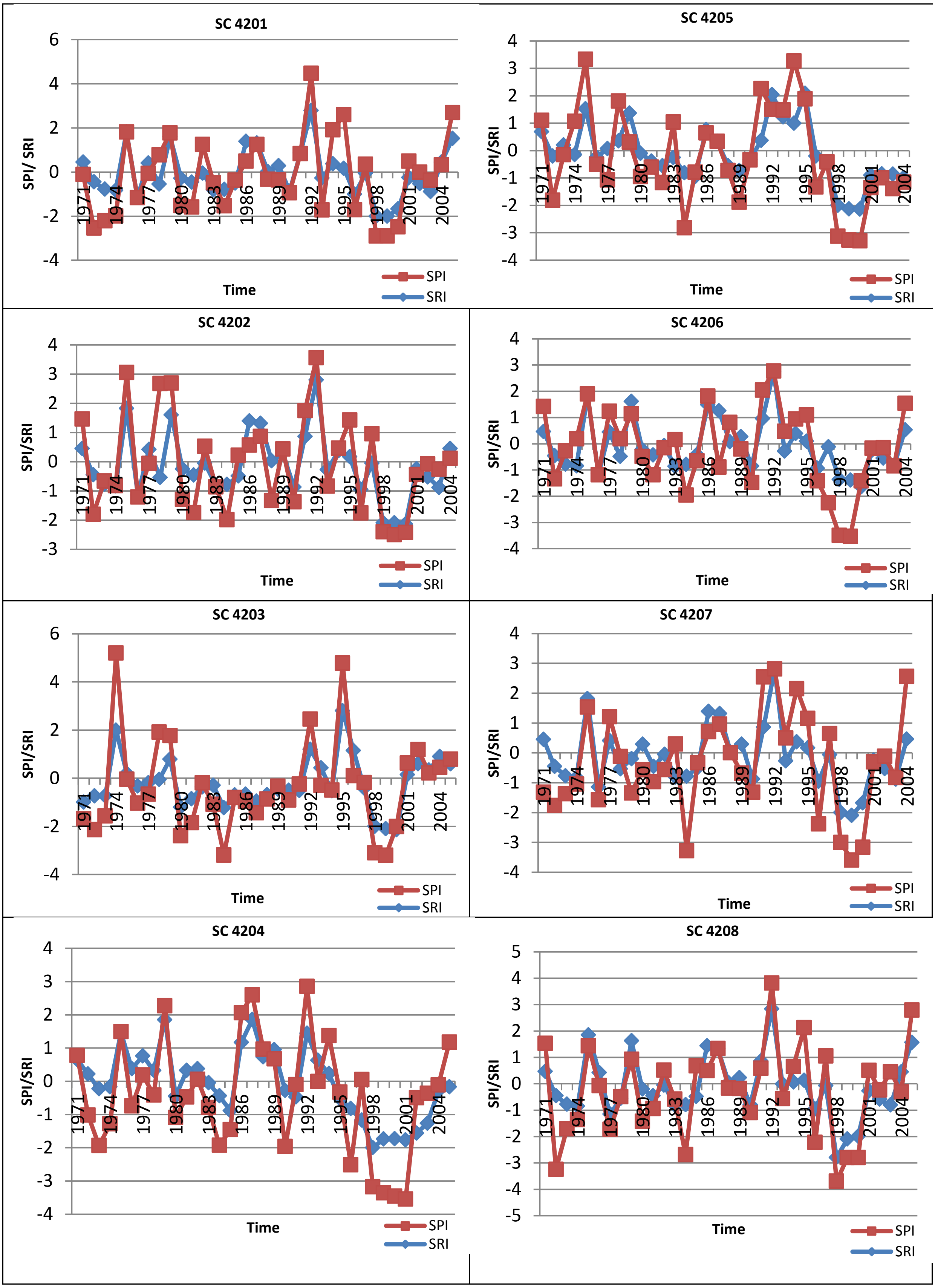


Figure 4.6: Time series of the 12 month SPI and SRI for sub-catchment of 4201 to 4208

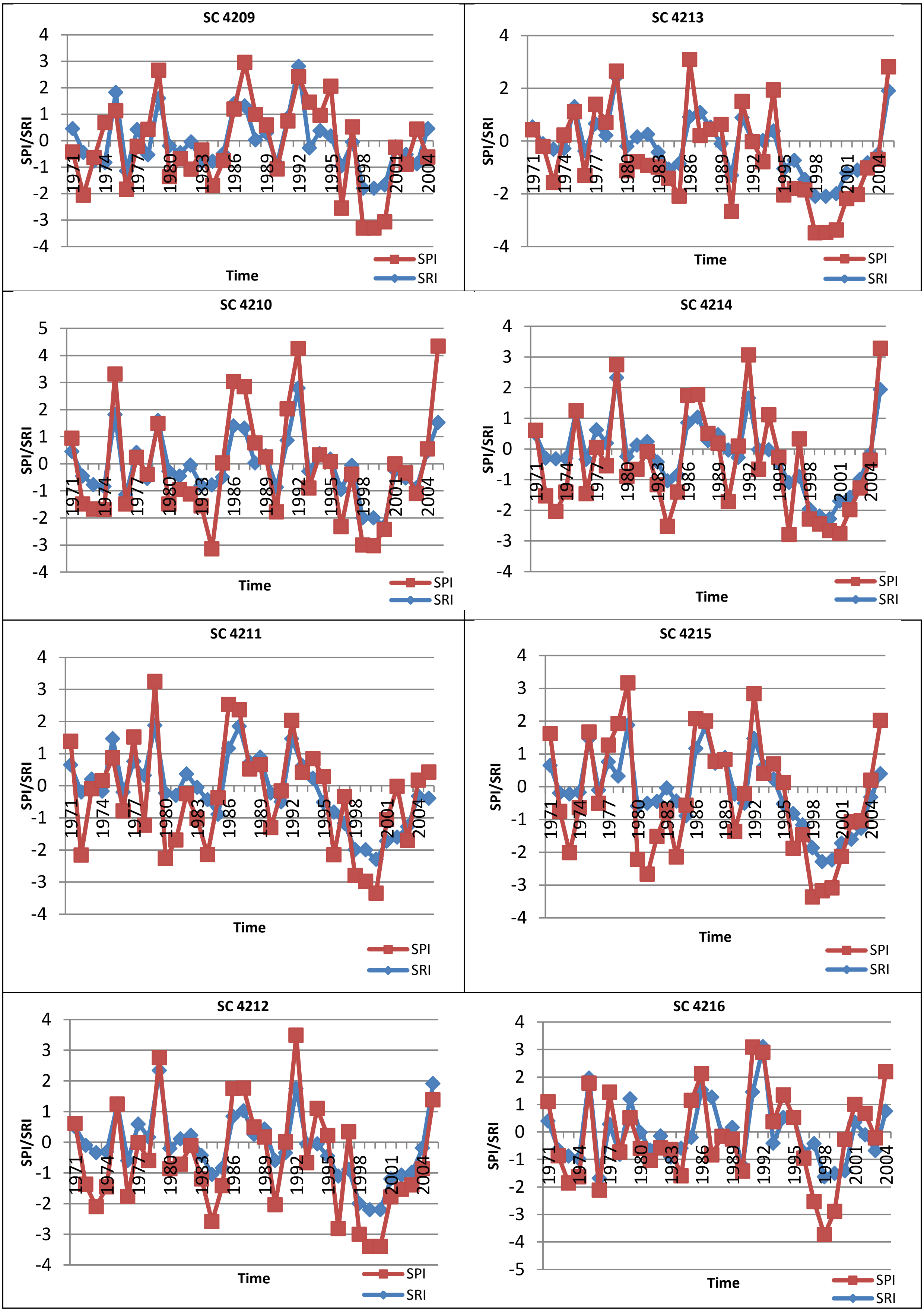


Figure 4.7: Time series of the 12 month SPI and SRI for sub-catchment of 4209 to 4216

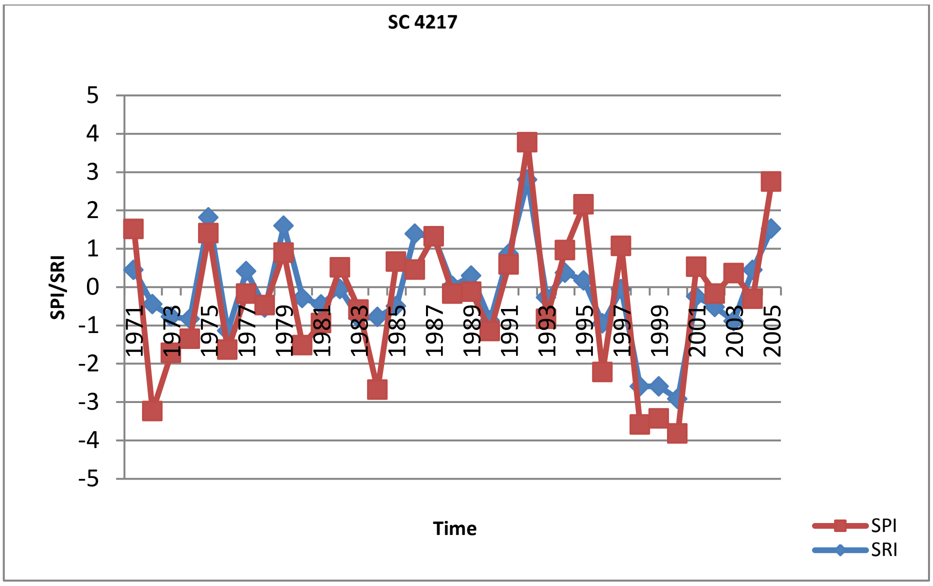


Figure 4.8: Time series of the 12 month SPI and SRI for sub-catchment of 4217

4.3.3 Drought characterization: the spatial and temporal resolution of SPI and SRI

The continuous precipitation data over a 30-year period from 17 rain-gauge stations in Zayandeh Rud basin have been reviewed. The appreciating probability distribution to SPI, the frequency distribution (histogram) and the cumulative probability distribution of the precipitation data, prior to their standardization from all stations were explored. The results of the SPI and SRI index for each sub-catchment in the 30-year time scale were transferred into spatial representations to map different drought. ArcGIS was used to map the spatial pattern of the significant meteorological drought and hydrological drought in the driest month in 1972, 1976, 1980, 1984, 1990, 1996, 1998, 1999 and 2000 at Zayandeh Rud basin. The resolution of data is 5km×5km with respect to the scale of the study area.

In these maps (Figures 4.9 to 4.11) the SPI and SRI classified into 5 levels, for each year. These maps were categorized into five levels of no dry, mild dry, moderately dry, severely dry, and extremely dry. The spatial distribution of drought indicates the most significant severe droughts occurred in 1976 (a duration of 2 to 6 months), 1980 (2 to 7 months) and 1996 (1 to 8 months). The driest month of meteorological drought for those years was April, January, and February, respectively. However, the driest month for hydrological drought was

July, August, and September. The most significant extreme drought occurred in 1972 (a duration of 2 to 5 months), 1998, 1999 and 2000 (2 to 12 months). The driest month of meteorological drought for those years was January, June, January, and March, respectively. However, the driest month for hydrological drought was July, October, October and October, respectively. Moreover, moderate drought occurred in 1990. The driest month of meteorological and hydrological drought for this year was February and April of 2 to 7 months.

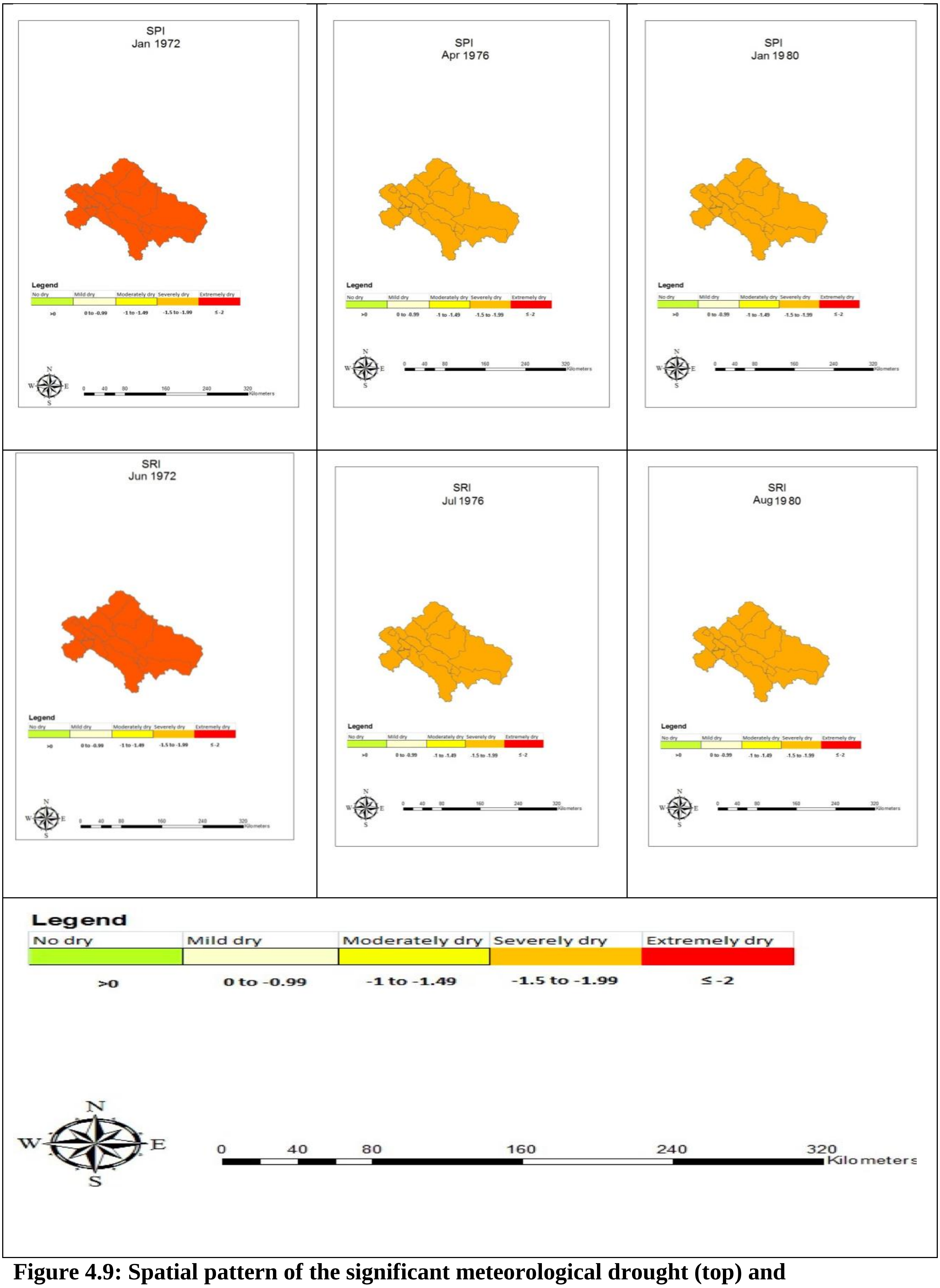


Figure 4.9: Spatial pattern of the significant meteorological drought (top) and hydrological drought (bottom) in driest month in 1972, 1976, 1980 at Zayandeh Rud basin

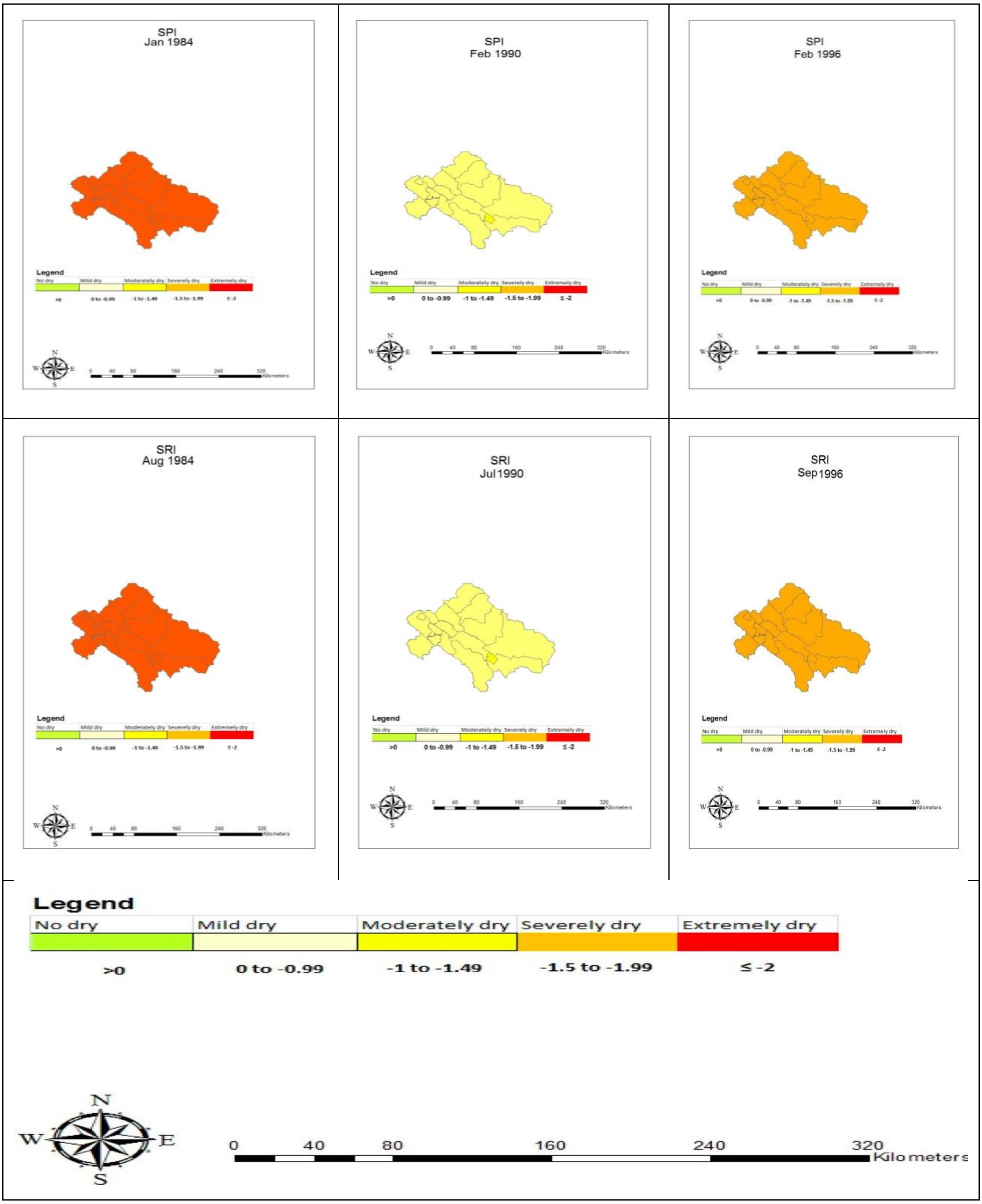


Figure 4.10: Spatial pattern of the significant meteorological drought (top) and hydrological drought (bottom) in driest month in 1984, 1990, 1996 at Zayandeh Rud basin

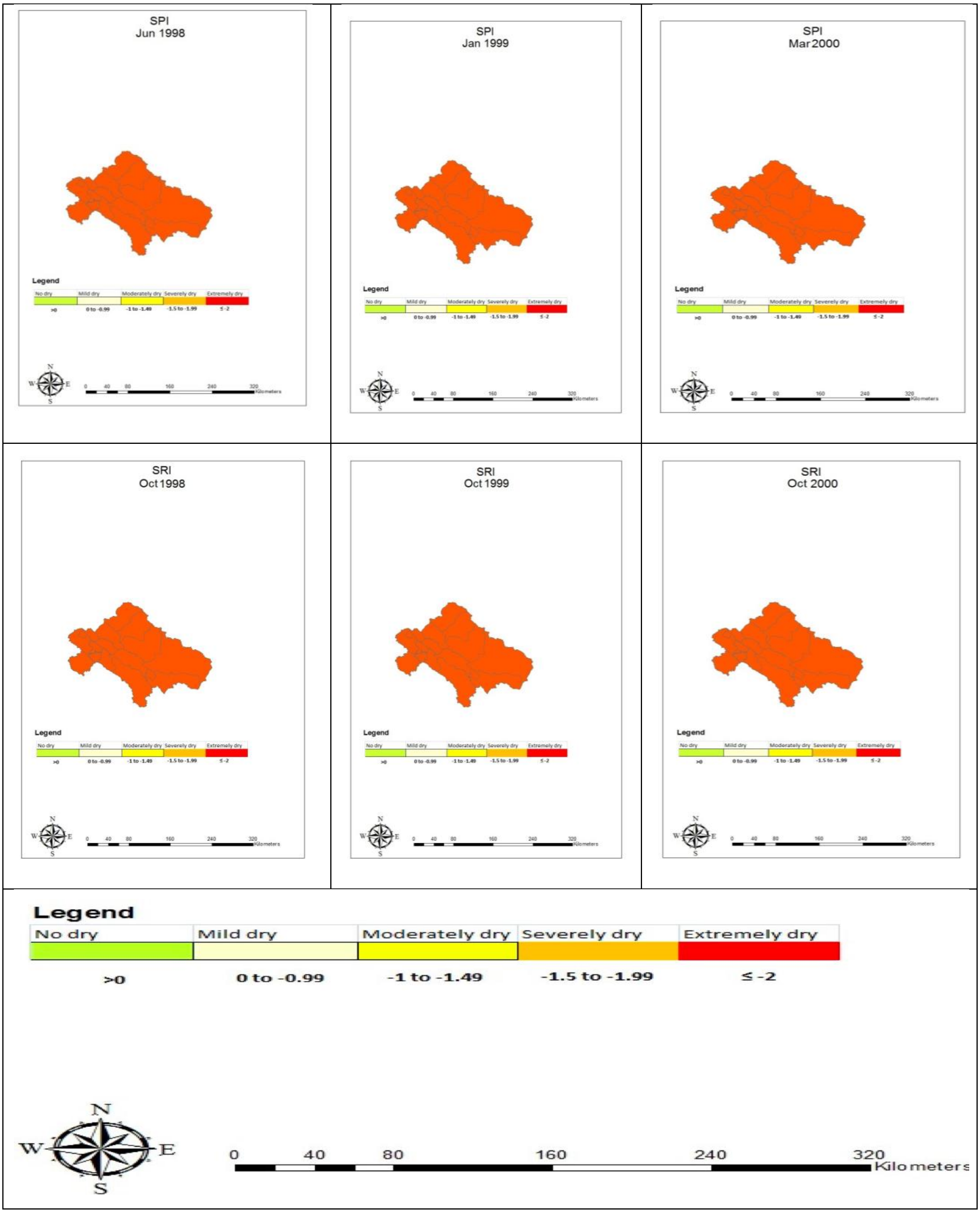


Figure 4.11: Spatial pattern of the significant meteorological drought (top) and hydrological drought (bottom) in driest month in 1998,1999, 2000 at Zayandeh Rud basin

4.3.4 Trend in drought characteristics

All stations show a period of a high frequency of droughts followed by some years of generally low precipitation. To better illustrate the differences between the drought indices and several seasons in different sub-catchments, a Mann-Kendall trend test was applied. The outputs of the significant trend tests (upward drought trend) on the SPI and SRI-12 series in 1971-2003 for each sub-catchment that used the Mann-Kendall test are shown in Tables 4.6, 4.7 and 4.8.

Tables 4.6, 4.7 and 4.8 provide the summary statistics including P values of the trends at 95% confidence level (0.05 significance level). Non-overlapping data samples are used for trend analysis to avoid serial dependencies. In general a statistically significant upward drought trend was found in the Zayandeh Rud basin. The most significant drying trend (the upward drought trend in SPI-12 and SRI-12 series) for both meteorological and hydrological drought is shown in all sub-catchments downstream and in the west part of the Zayandeh Rud basin. Only in sub-catchments 4210, 4211, 4212, 4213, 4214 and 4215, which are located upstream and near mountainous regions and receive more precipitation, is there no significant annual drought. Two climate signals, ENSO and NAO and the Mediterranean system can affect climate variation, rainfall and stream flow of the rivers in the Zayandeh Rud basin (Araghinejad et al., 2006).

The decreasing trend in the rainfall series downstream and in the east part of the Zayandeh Rud basin probably causes the significant upward drying trend. It was detected at 95% significant level for meteorological and hydrological drought in those sub-catchments. This analysis shows the most arid regions are getting more arid.

In all stations, the significant upward meteorological drought trend was found in winter and spring. However, the significant hydrological upward droughts were detected in autumn and summer. For instance, the most significant meteorological drought of all 17 stations of 1999 and 2000 occurred in January and March. While the most significant hydrological drought for all stations occurred in October. The results annual and seasonal, for the sub-catchments, are mapped in Figure 4.12.

Table 4.6: The result of the Mann-Kendall trend test for the time series of meteorological and hydrological drought indices in the Zayandeh Rud sub-basins (*when the p-values < 0.05, there is a significant upward trend for droughts).

Region	Index	H(0)	P value	Trend
Zayandeh Rud basin	SPI	True	0.025 *	Yes
	SRI	True	0.030*	Yes
4201	SPI	True	0.048*	Yes
	SRI	True	0.041*	Yes
4202	SPI	True	0.048*	Yes
	SRI	True	0.041*	Yes
4203	SPI	True	0.024*	Yes
	SRI	True	0.030*	Yes
4204	SPI	True	0.001*	Yes
	SRI	True	0.017*	Yes
4205	SPI	True	0.024*	Yes
	SRI	True	0.048*	Yes
4206	SPI	True	0.028*	Yes
	SRI	True	0.046*	Yes
4207	SPI	True	0.016*	Yes
	SRI	True	0.016*	Yes
4208	SPI	True	0.00*	Yes
	SRI	True	0.042*	Yes
4209	SPI	True	0.018*	Yes
	SRI	True	0.040*	Yes
4210	SPI	False	0. 11	No
	SRI	False	0.90	No
4211	SPI	False	0.99	No
	SRI	False	1	No
4212	SPI	False	0.99	No
	SRI	False	0.80	No
4213	SPI	False	0.90	No
	SRI	False	0.97	No
4214	SPI	False	1	No
	SRI	False	0.98	No
4215	SPI	False	0.90	No
	SRI	False	0.83	No
4216	SPI	False	0.80	No
	SRI	False	0.83	No
4217	SPI	True	0.01	Yes
	SRI	True	0.04	Yes

Table 4.7: The result of the Mann-Kendall trend test for the annual and seasonal time series of the meteorological drought index (SPI) in the sub-catchments of Zayandeh rud basin (*and yellow colour when the p-values < 0.05, there is a significant upward trend for droughts)

Sub-basin	Annual(Oct-Sep)	Autumn(Oct-Dec)	Winter(Jan-Mar)	Spring (Apr-Jun)	Summer (Jul-Sep)
4201	0.048*	0.48	0.040*	0.037*	0.52
4202	0.048*	0.49	0.024*	0.019*	0.24
4203	0.024*	0.45	0.041*	0.039*	0.27
4204	0.010*	0.15	0.010*	0.0001*	0.240
4205	0.024*	0.33	0.024*	0.017*	0.39
4206	0.028*	0.32	0.043*	0.025*	0.30
4207	0.016*	0.26	0.044*	0.036*	0.12
4208	0*	0.2	0.014*	0.01*	0.05
4209	0.018*	0.36	0.40*	0.036*	0.05
4210	0.11	0.20	0.04*	0.016*	0.92
4211	0.10	0.90	0.03*	0.01*	0.88
4212	0.10	0.2	0.02*	0.01*	0.36
4213	0.11	0.70	0.02*	0.01*	0.63
4214	0.10	0.15	0.02*	0.01*	0.24
4215	0.10	0.90	0.02*	0*	0.88
4216	0.8	0.90	0.007*	0.001*	0.90
4217	0.01*	0.02*	0.018*	0.04*	0.05

Table 4.8: The result of the Mann-Kendall trend test for the annual time series of the hydrological drought index (SRI) in the sub-catchments of Zayandeh Rud basin (* When the p-values < 0.05, there is a significant upward trend for droughts)

Sub-basin	Annual(Oct-Sep)	Autumn(Oct-Dec)	Winter(Jan-Mar)	Spring (Apr-Jun)	Summer (Jul-Sep)
4201	0.041*	0.023*	0.45	0.47	0.015*
4202	0.041*	0.028*	0.45	0.53	0.028*
4203	0.030*	0.04*	0.10	0.27	0.018*
4204	0.017*	0.0001*	0.20	0.39	0.001*
4205	0.010*	0.043*	0.97	0.72	0.01*
4206	0.046*	0.029*	0.45	0.47	0.018*
4207	0.016*	0.026*	0.36	0.44	0.012*
4208	0.042*	0.025*	0.45	0.48	0.014*
4209	0.040*	0.022*	0.36	0.38	0.022*
4210	0.50	0*	0.57	0.57	0.01*
4211	0.41	0.01*	0.59	0.57	0*
4212	0.48	0.012*	0.59	0.52	0.01*
4213	0.50	0.02*	0.59	0.40	0.01*
4214	0.48	0.017*	0.6	0.69	0.01*
4215	0.53	0.048*	0.80	0.07	0.01*
4216	0.48	0.013	0.58	0.52	0.048*
4217	0.04*	0.022*	0.046*	0.047*	0.028*

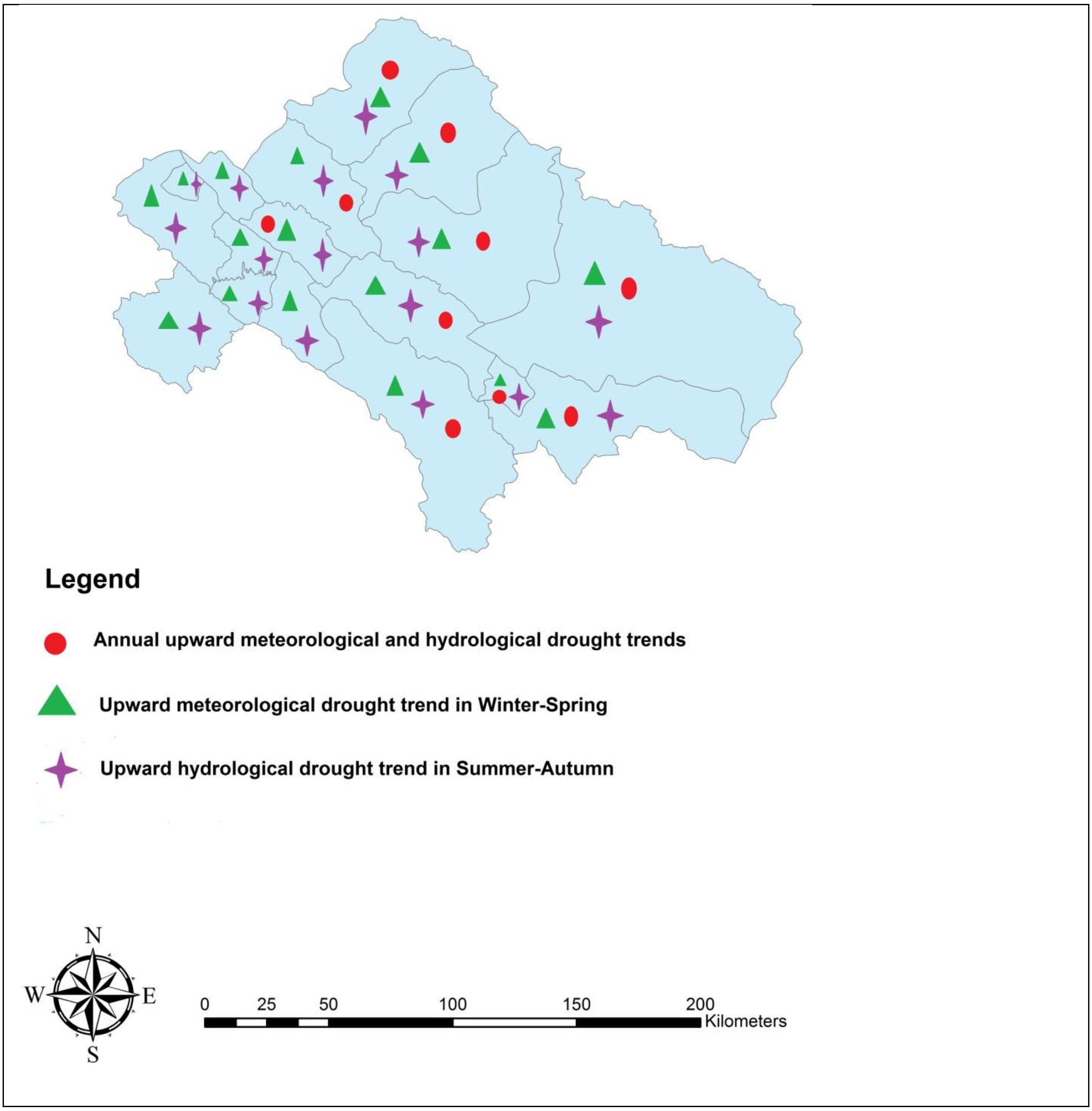


Figure 4.12: Annual and seasonal upward drought trends (the points show the existence upward drought trends in the sub-catchments)

4.3.5 Intensity-duration-frequency analysis of droughts

The main characteristics of the significant meteorological and hydrological droughts in 1972, 1976, 1980, 1984, 1990, 1996, 1998, 1999 and 2000 are given in Tables 4.9, 4.10, 4.11, 4.12, 4.13, 4.14, 4.15, 4.16 and 4.17. The spatial patterns of the minimum drought indices are mapped in Figures 4.13 to 4.21. It can be seen that at least one severe drought occurred at all the stations. The most severe drought occurred between 1998 and 2000. Generally for all drought years, the most severe drought occurred at the East and South part of the basin. For example, sub-basins 420, 4202 and 4217 experienced minimum SPI-12 and SRI-12 of -1.96 and -1.69 in March and October 2000. However, sub-basin 4216 (in the West and upstream of the basin) experienced an SPI-12 and SRI-12 of -1.21 and -1.15 in March and October 2000. The results indicated that the longest duration of the drought at the stations was 4-6 months for SPI and 12 months for SRI.

Table 4.9: Characteristics of droughts at 12-month timescale for the year of 1972

Sub-basin	Drought Index	Min index	Driest month	Maximum duration (month)
4201	SPI	-1.21	Jan	4
	SRI	-0.74	Jul	4
4202	SPI	-1.35	Jan	4
	SRI	-0.96	Jul	5
4203	SPI	-1.40	Jan	2
	SRI	-0.74	Jul	5
4204	SPI	-1.2	Jan	2
	SRI	-0.42	Jul	3
4205	SPI	-1.43	Jan	3
	SRI	-0.74	Jul	3
4206	SPI	-1.40	Jan	3
	SRI	-0.71	Jul	5
4207	SPI	-1.35	Jan	3
	SRI	-0.71	Jul	5
4208	SPI	-1.30	Jan	3
	SRI	-0.71	Jul	5
4209	SPI	-1.46	Jan	2
	SRI	-0.71	Jul	5
4210	SPI	-1.03	Jan	2
	SRI	-0.79	Jul	5
4211	SPI	-1	Jan	3
	SRI	-0.43	Jul	3
4212	SPI	-1.14	Jan	2
	SRI	-0.52	Jul	5
4213	SPI	-1.14	Jan	2
	SRI	-0.50	Jul	5
4214	SPI	-1.19	Jan	2
	SRI	-0.63	Jul	4
4215	SPI	-1	Jan	2
	SRI	-0.41	Jul	3
4216	SPI	-1.11	Jan	2
	SRI	-0.46	Jul	5
4217	SPI	-1.30	Jan	4
	SRI	-0.75	Jul	5

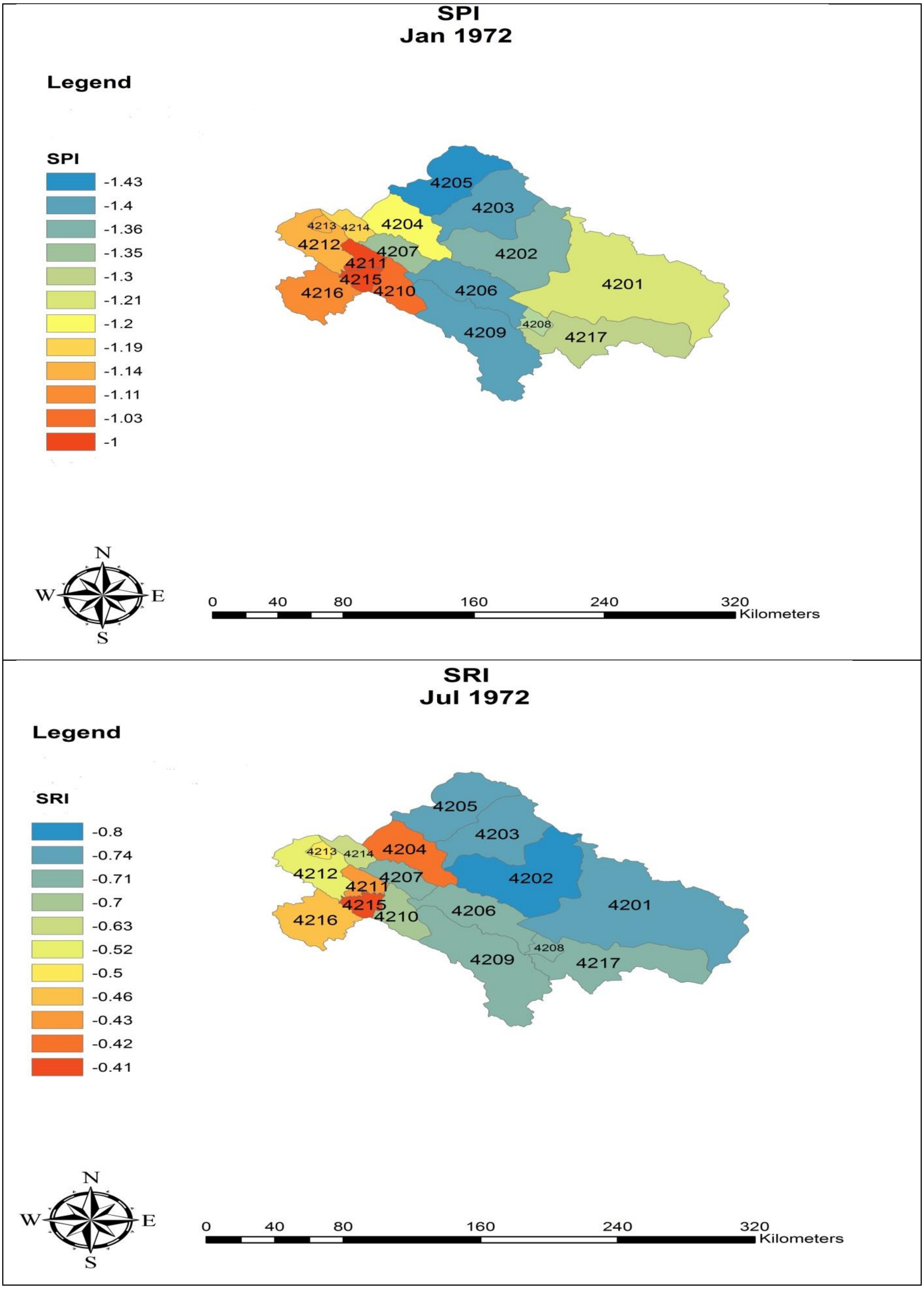


Figure 4.13: Spatial pattern of minimum drought indices during 1972 drought

Table 4.10: Characteristics of droughts at 12-month timescale for the year of 1976

Sub-basin	Drought Index	Min index	Driest month	Maximum duration (month)
4201	SPI	-1.34	Apr	4
	SRI	-1.14	Jul	4
4202	SPI	-1.34	Apr	4
	SRI	-1.14	Jul	4
4203	SPI	-1.34	Apr	3
	SRI	-1.14	Jul	4
4204	SPI	-1.20	Apr	2
	SRI	-1.00	Jul	2
4205	SPI	-1.34	Apr	3
	SRI	-1.14	Jul	5
4206	SPI	-1.30	Apr	5
	SRI	-1.09	Jul	5
4207	SPI	-1.20	Apr	4
	SRI	-1.08	Jul	4
4208	SPI	-1.37	Apr	4
	SRI	-1.15	Jul	5
4209	SPI	-1.30	Apr	5
	SRI	-1.09	Jul	5
4210	SPI	-1.30	Apr	5
	SRI	-1.08	Jul	5
4211	SPI	-1.20	Apr	2
	SRI	-1	Jul	2
4212	SPI	-1.17	Apr	2
	SRI	-1	Jul	4
4213	SPI	-1.17	Apr	5
	SRI	-1	Jul	6
4214	SPI	-1.17	Apr	5
	SRI	-1	Jul	6
4215	SPI	-1.20	Apr	2
	SRI	-1	Jul	3
4216	SPI	-1.17	Apr	5
	SRI	-1.04	Jul	6
4217	SPI	-1.18	Apr	4
	SRI	-1.14	Jul	6

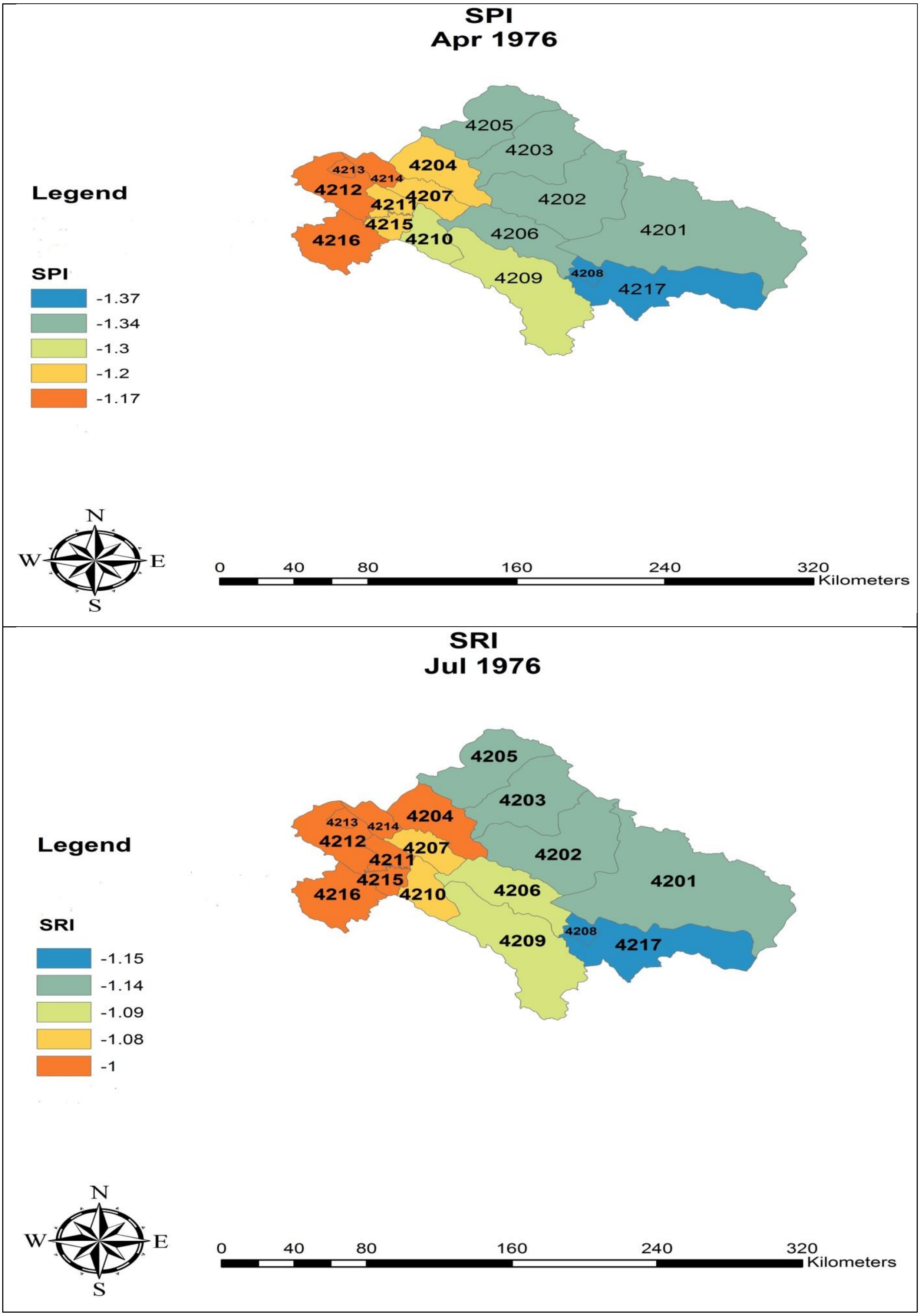


Figure 4.14: Spatial pattern of minimum drought indices during 1976 drought

Table 4.11: Characteristics of droughts at 12-month timescale for the year of 1980

Sub-basin	Drought Index	Min index	Driest month	Maximum duration (month)
4201	SPI	-1.23	Jan	2
	SRI	-0.65	Aug	6
4202	SPI	-1.23	Jan	2
	SRI	-0.65	Aug	2
4203	SPI	-1.23	Jan	4
	SRI	-0.53	Aug	5
4204	SPI	-1.04	Jan	3
	SRI	-0.35	Aug	3
4205	SPI	-1.23	Jan	4
	SRI	-0.53	Aug	7
4206	SPI	-1.20	Jan	4
	SRI	-0.65	Aug	6
4207	SPI	-1.00	Jan	3
	SRI	-0.49	Aug	6
4208	SPI	-1.20	Jan	3
	SRI	-0.65	Aug	6
4209	SPI	-1.20	Jan	4
	SRI	-0.65	Aug	5
4210	SPI	-1.11	Jan	4
	SRI	-0.49	Aug	7
4211	SPI	-1.11	Jan	3
	SRI	-0.42	Aug	5
4212	SPI	-1.10	Jan	3
	SRI	-0.2	Aug	5
4213	SPI	-1.11	Jan	4
	SRI	-0.35	Aug	5
4214	SPI	-1.11	Jan	2
	SRI	-0.35	Aug	6
4215	SPI	-1.11	Jan	2
	SRI	-0.42	Aug	5
4216	SPI	-1.10	Jan	2
	SRI	-0.2	Aug	6
4217	SPI	-1.20	Jan	2
	SRI	-0.65	Aug	5

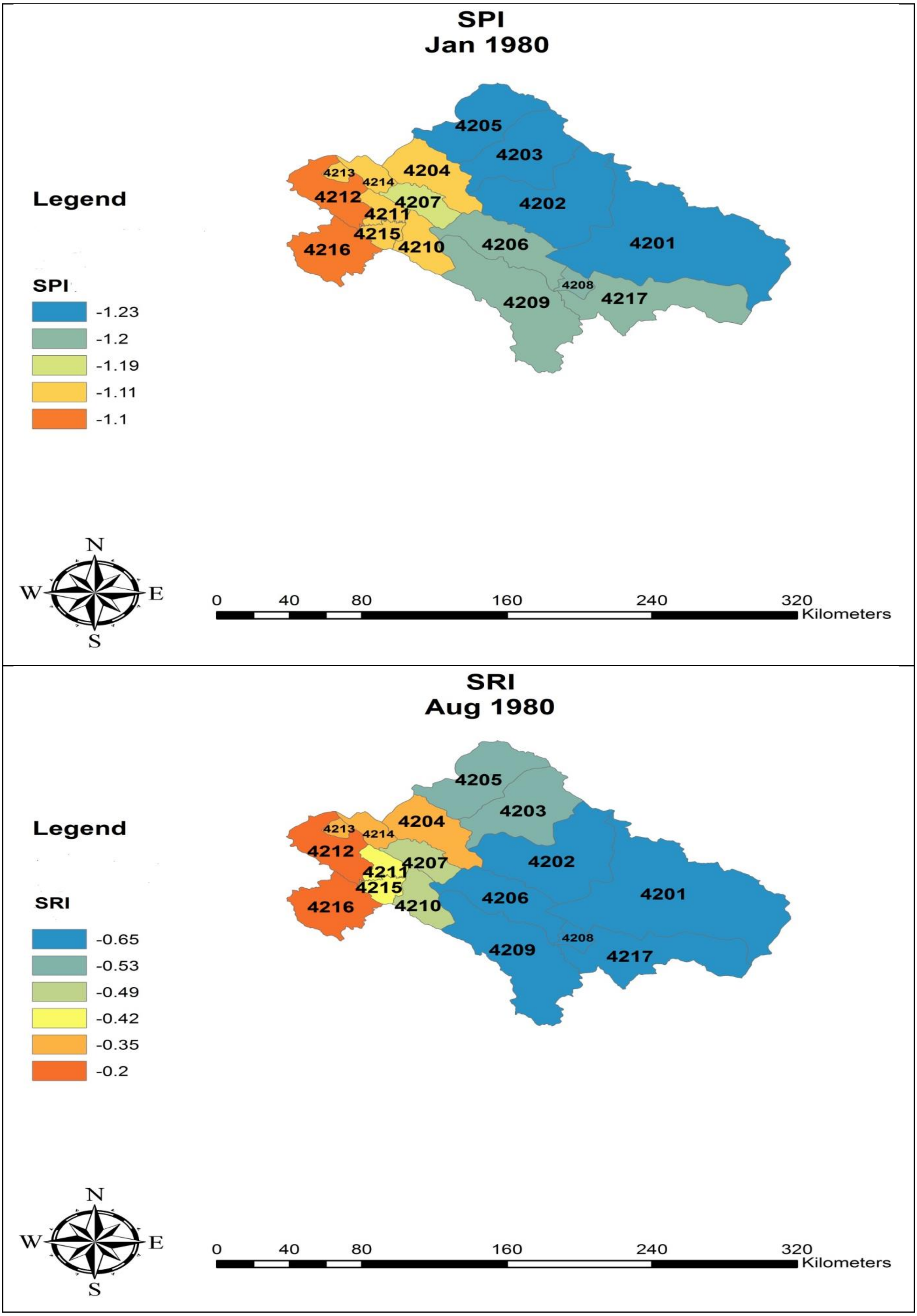


Figure 4.15: Spatial pattern of minimum drought indices during 1980 drought

Table 4.12: Characteristics of droughts at 12-month timescale for the year of 1984

Sub-basin	Drought Index	Min index	Driest month	Maximum duration (month)
4201	SPI	-1.39	Jan	2
	SRI	-0.98	Aug	4
4202	SPI	-1.40	Jan	2
	SRI	-0.98	Aug	5
4203	SPI	-1.40	Jan	2
	SRI	-0.96	Aug	2
4204	SPI	-1.11	Jan	3
	SRI	-0.76	Aug	6
4205	SPI	-1.40	Jan	2
	SRI	-0.96	Aug	6
4206	SPI	-1.20	Jan	4
	SRI	-0.90	Aug	6
4207	SPI	-1.20	Jan	4
	SRI	-0.90	Aug	6
4208	SPI	-1.39	Jan	4
	SRI	-0.60	Aug	7
4209	SPI	-1.16	Jan	3
	SRI	-0.83	Aug	6
4210	SPI	-1.16	Jan	4
	SRI	-0.83	Aug	5
4211	SPI	-1.13	Jan	4
	SRI	-0.70	Aug	7
4212	SPI	-1.13	Jan	2
	SRI	-0.50	Aug	3
4213	SPI	-1.13	Jan	4
	SRI	-0.70	Aug	7
4214	SPI	-1.11	Jan	3
	SRI	-0.76	Aug	6
4215	SPI	-1.06	Jan	2
	SRI	-0.70	Aug	7
4216	SPI	-1.06	Jan	2
	SRI	-0.5	Aug	7
4217	SPI	-1.39	Jan	4
	SRI	-0.98	Aug	7

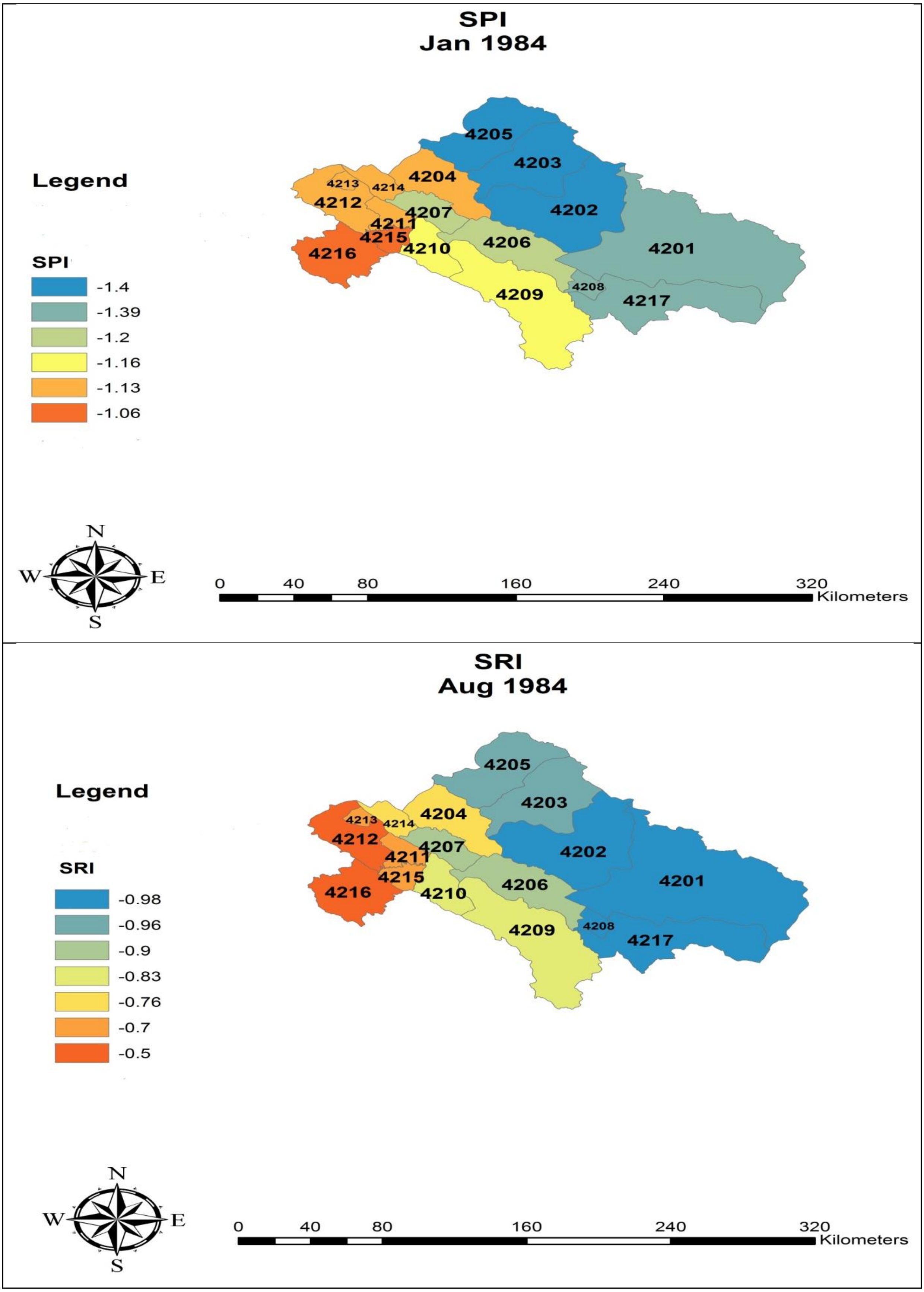


Figure 4.16: Spatial pattern of minimum drought indices during 1984 drought

Table 4.13: Characteristics of droughts at 12-month timescale for the year of 1990

Sub-basin	Drought Index	Min index	Driest month	Maximum duration (month)
4201	SPI	-1.36	Feb	2
	SRI	-1.25	Jul	3
4202	SPI	-1.36	Feb	3
	SRI	-1.25	Jul	3
4203	SPI	-1.36	Feb	2
	SRI	-1.25	Jul	3
4204	SPI	-1.16	Feb	6
	SRI	-1.14	Jul	6
4205	SPI	-1.36	Feb	7
	SRI	-1.25	Jul	7
4206	SPI	-1.25	Feb	5
	SRI	-1.14	Jul	6
4207	SPI	-1.25	Feb	5
	SRI	-1.14	Jul	6
4208	SPI	-1.34	Feb	5
	SRI	-1.25	Jul	6
4209	SPI	-1.30	Feb	6
	SRI	-1.25	Jul	6
4210	SPI	-1.14	Feb	5
	SRI	-1.00	Jul	5
4211	SPI	-1.14	Feb	4
	SRI	-0.88	Jul	5
4212	SPI	-1.16	Feb	4
	SRI	-0.88	Jul	6
4213	SPI	-1.16	Feb	5
	SRI	-1.36	Jul	5
4214	SPI	-1.16	Feb	6
	SRI	-1.14	Jul	6
4215	SPI	-1.14	Feb	5
	SRI	-0.88	Jul	5
4216	SPI	-1.00	Feb	4
	SRI	-0.86	Jul	5
4217	SPI	-1.34	Feb	5
	SRI	-1.25	Jul	5

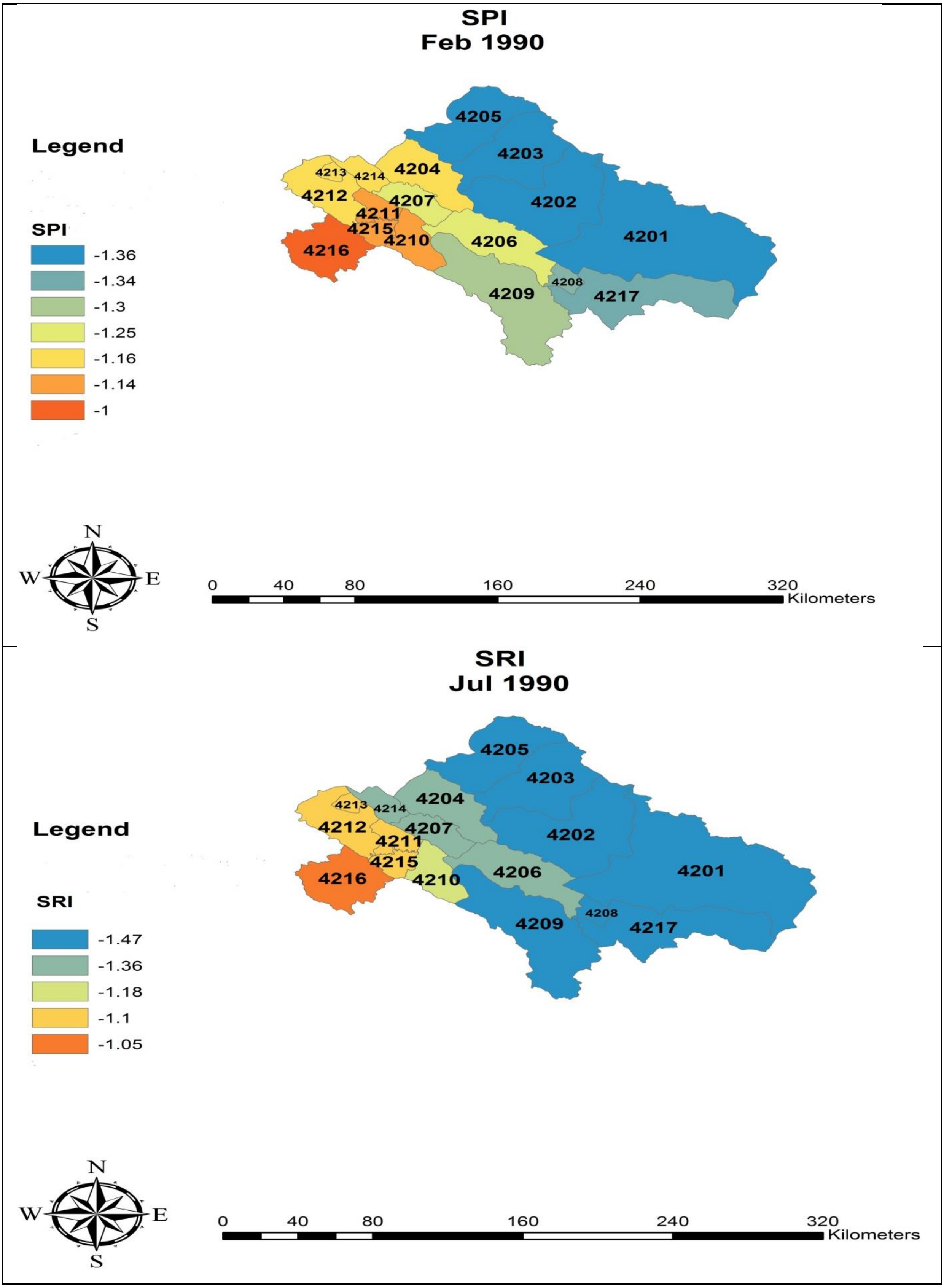


Figure 4.17: Spatial pattern of minimum drought indices during 1990 drought

Table 4.14: Characteristics of droughts at 12-month timescale for the year of 1996

Sub-basin	Drought Index	Min index	Driest month	Maximum duration (month)
4201	SPI	-1.44	Feb	2
	SRI	-1.05	Sep	4
4202	SPI	-1.44	Feb	3
	SRI	-1.27	Sep	6
4203	SPI	-1.44	Feb	3
	SRI	-1.27	Sep	3
4204	SPI	-1.30	Feb	3
	SRI	-1.17	Sep	5
4205	SPI	-1.30	Feb	3
	SRI	-1.27	Sep	4
4206	SPI	-1.36	Feb	3
	SRI	-1.17	Sep	6
4207	SPI	-1.36	Feb	3
	SRI	-1.17	Sep	4
4208	SPI	-1.46	Feb	2
	SRI	-1.27	Sep	6
4209	SPI	-1.36	Feb	1
	SRI	-1.07	Sep	4
4210	SPI	-1.30	Feb	2
	SRI	-1.07	Sep	4
4211	SPI	-1.22	Feb	3
	SRI	-1.05	Sep	3
4212	SPI	-1.17	Feb	3
	SRI	-1.05	Sep	6
4213	SPI	-1.17	Feb	2
	SRI	-1.05	Sep	6
4214	SPI	-1.17	Feb	3
	SRI	-1.05	Sep	6
4215	SPI	-1.17	Feb	3
	SRI	-1.05	Sep	7
4216	SPI	-1.13	Feb	1
	SRI	-1.00	Sep	8
4217	SPI	-1.46	Feb	2
	SRI	-1.27	Sep	7

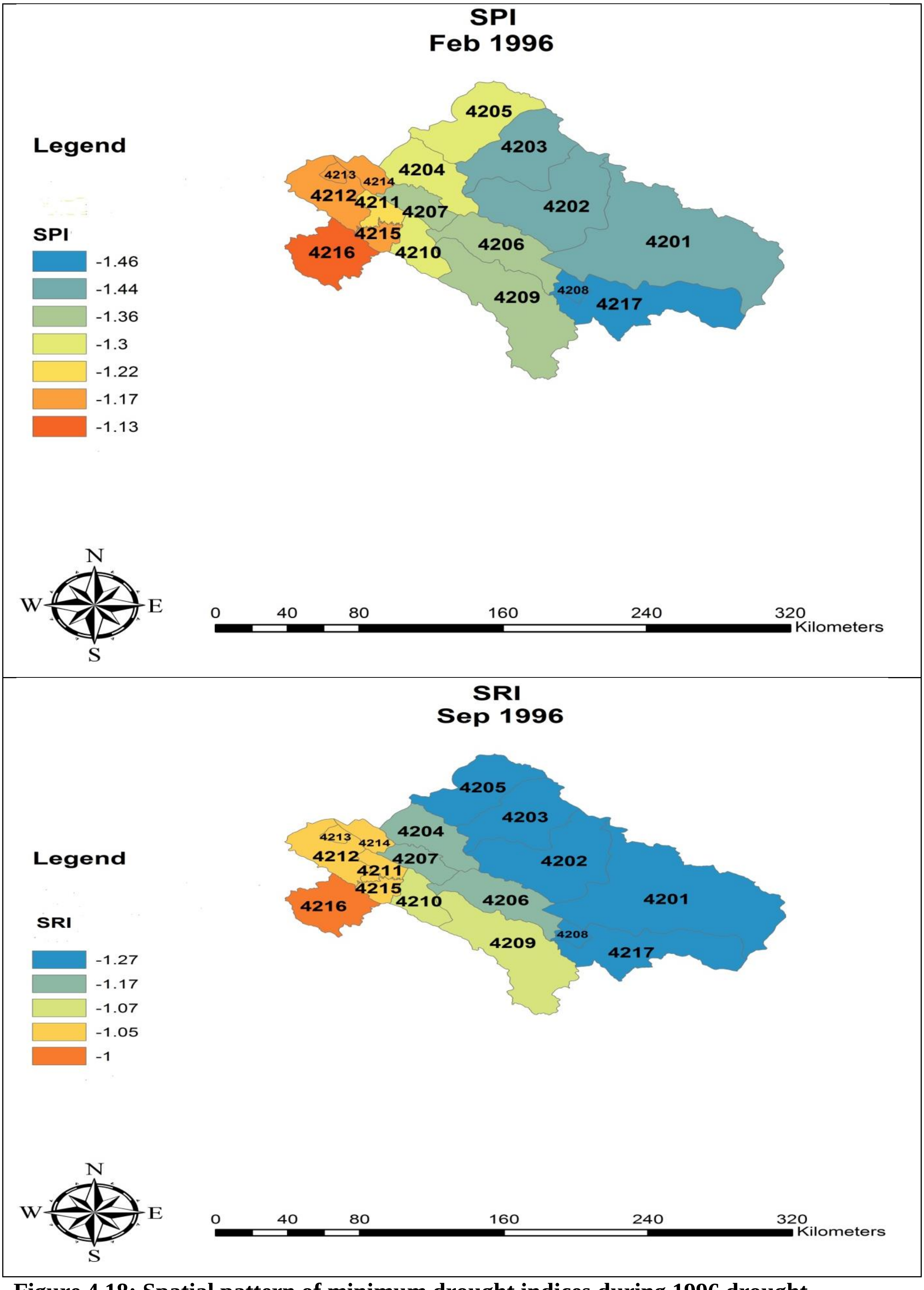


Figure 4.18: Spatial pattern of minimum drought indices during 1996 drought

Table 4.15: Characteristics of droughts at 12-month timescale for the year of 1998

Sub-basin	Drought Index	Min index	Driest month	Maximum duration (month)
4201	SPI	-1.48	Jun	4
	SRI	-1.25	Oct	10
4202	SPI	-1.48	Jun	5
	SRI	-1.25	Oct	8
4203	SPI	-1.46	Jun	2
	SRI	-1.25	Oct	3
4204	SPI	-1.46	Jun	5
	SRI	-1.25	Oct	7
4205	SPI	-1.46	Jun	8
	SRI	-1.25	Oct	12
4206	SPI	-1.42	Jun	6
	SRI	-1.22	Oct	12
4207	SPI	-1.42	Jun	5
	SRI	-1.18	Oct	12
4208	SPI	1.45	Jun	5
	SRI	-1.25	Oct	12
4209	SPI	-1.42	Jun	7
	SRI	-1.22	Oct	12
4210	SPI	-1.40	Jun	8
	SRI	-1.15	Oct	12
4211	SPI	-1.40	Jun	7
	SRI	-1	Oct	7
4212	SPI	-1.25	Jun	4
	SRI	-1	Oct	7
4213	SPI	-1.25	Jun	5
	SRI	-1	Oct	7
4214	SPI	-1.42	Jun	5
	SRI	-1.18	Oct	4
4215	SPI	-1.40	Jun	3
	SRI	-1	Oct	6
4216	SPI	-1.25	Jun	2
	SRI	-1.00	Oct	11
4217	SPI	-1.45	Jun	6
	SRI	-1.25	Oct	11

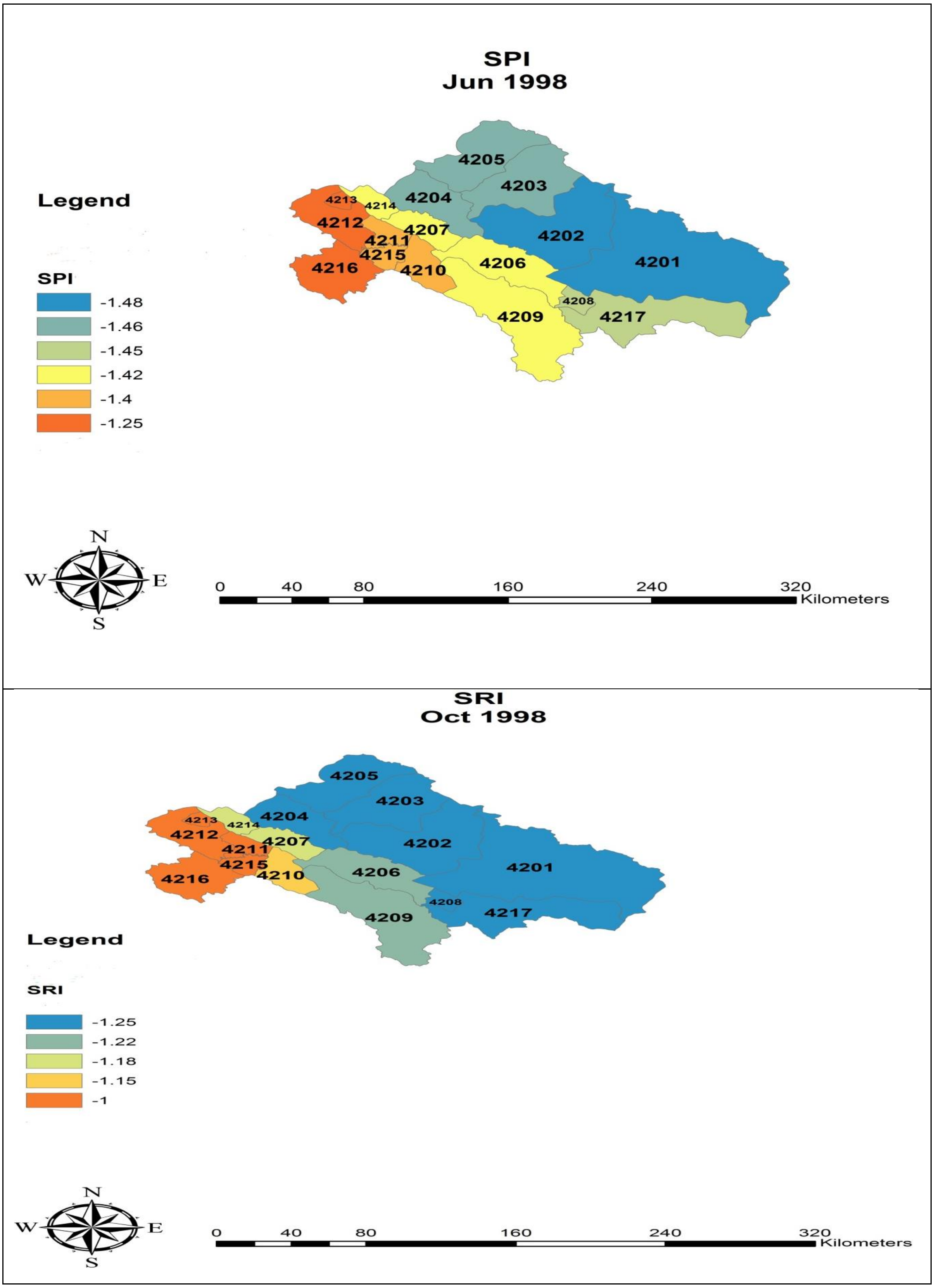


Figure 4.19: Spatial pattern of minimum drought indices during 1998 drought

Table 4.16: Characteristics of droughts at 12-month timescale for the year of 1999

Sub-basin	Drought Index	Min index	Driest month	Maximum duration (month)
4201	SPI	-1.48	Jan	4
	SRI	-1.45	Oct	10
4202	SPI	-1.48	Jan	2
	SRI	-1.45	Oct	8
4203	SPI	-1.47	Jan	3
	SRI	-1.45	Oct	3
4204	SPI	-1.47	Jan	5
	SRI	-1.45	Oct	7
4205	SPI	-1.47	Jan	5
	SRI	-1.45	Oct	12
4206	SPI	-1.46	Jan	5
	SRI	-1.41	Oct	12
4207	SPI	-1.46	Jan	5
	SRI	-1.47	Oct	12
4208	SPI	-1.46	Jan	5
	SRI	-1.45	Oct	12
4209	SPI	-1.46	Jan	4
	SRI	-1.38	Oct	11
4210	SPI	-1.46	Jan	5
	SRI	-1.38	Oct	11
4211	SPI	-1.46	Jan	3
	SRI	-1.39	Oct	7
4212	SPI	-1.46	Jan	4
	SRI	-1.37	Oct	8
4213	SPI	-1.46	Jan	4
	SRI	-1.37	Oct	7
4214	SPI	-1.46	Jan	4
	SRI	-1.39	Oct	7
4215	SPI	-1.46	Jan	3
	SRI	-1.39	Oct	7
4216	SPI	-1.38	Jan	2
	SRI	-1.37	Oct	7
4217	SPI	-1.46	Jan	5
	SRI	-1.45	Oct	11

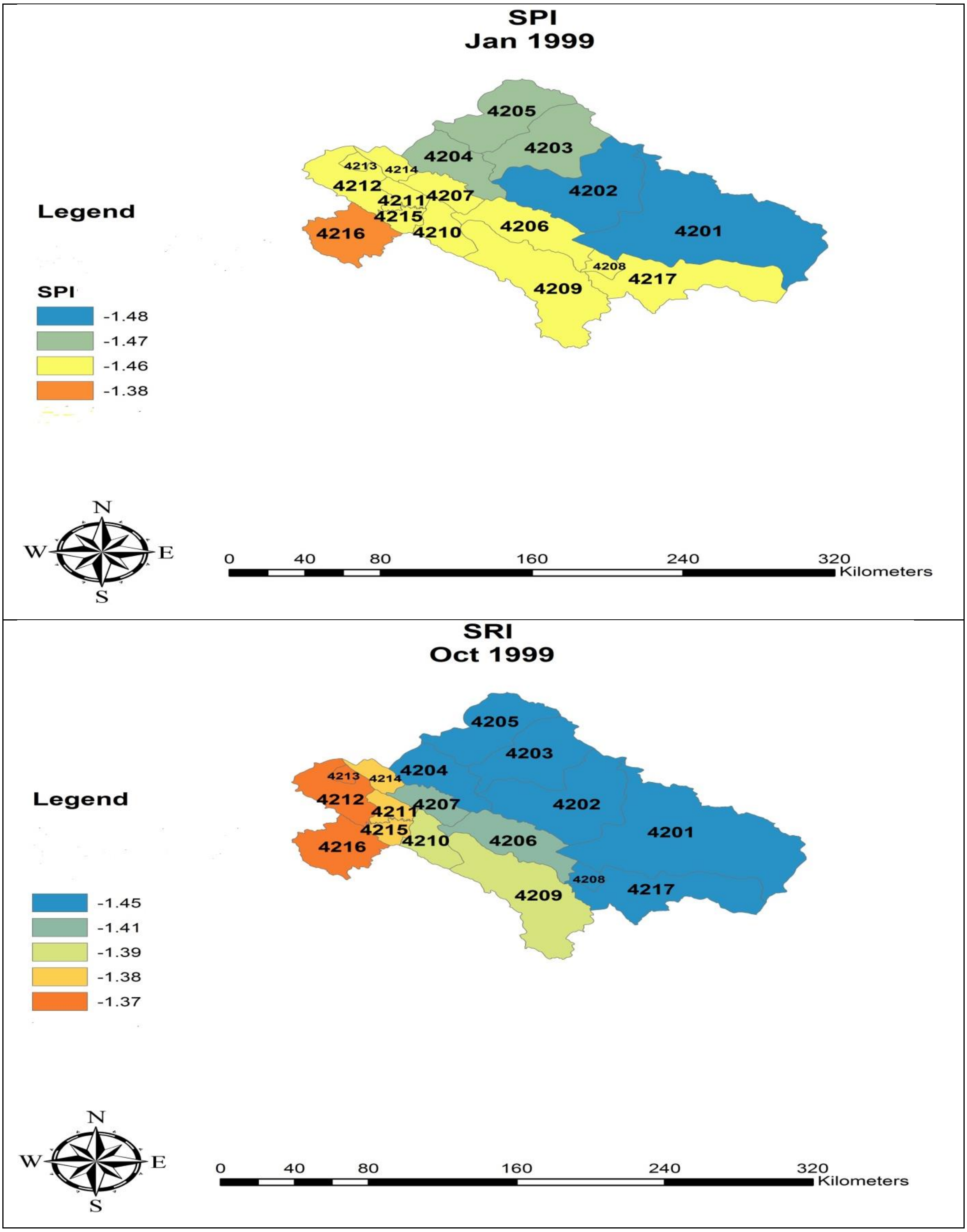


Figure 4.20: Spatial pattern of minimum drought indices during 1999 drought

Table 4.17: Characteristics of droughts at 12-month timescale for the year of 2000

Sub-basin	Drought Index	Min index	Driest month	Maximum duration (month)
4201	SPI	-1.96	Mar	4
	SRI	-1.69	Oct	12
4202	SPI	-1.96	Mar	2
	SRI	-1.69	Oct	4
4203	SPI	-1.95	Mar	4
	SRI	-1.69	Oct	4
4204	SPI	-1.72	Mar	4
	SRI	-1.48	Oct	7
4205	SPI	-1.95	Mar	7
	SRI	-1.69	Oct	7
4206	SPI	-1.72	Mar	7
	SRI	-1.48	Oct	11
4207	SPI	-1.72	Mar	7
	SRI	-1.48	Oct	12
4208	SPI	-1.96	Mar	6
	SRI	-1.69	Oct	11
4209	SPI	-1.83	Mar	8
	SRI	-1.47	Oct	11
4210	SPI	-1.83	Mar	7
	SRI	-1.47	Oct	12
4211	SPI	-1.57	Mar	4
	SRI	-1.19	Oct	7
4212	SPI	-1.54	Mar	6
	SRI	-1.15	Oct	8
4213	SPI	-1.54	Mar	6
	SRI	-1.15	Oct	6
4214	SPI	-1.62	Mar	4
	SRI	-1.48	Oct	8
4215	SPI	-1.57	Mar	6
	SRI	-1.19	Oct	7
4216	SPI	-1.21	Mar	6
	SRI	-1.15	Oct	6
4217	SPI	-1.96	Mar	6
	SRI	-1.69	Oct	12

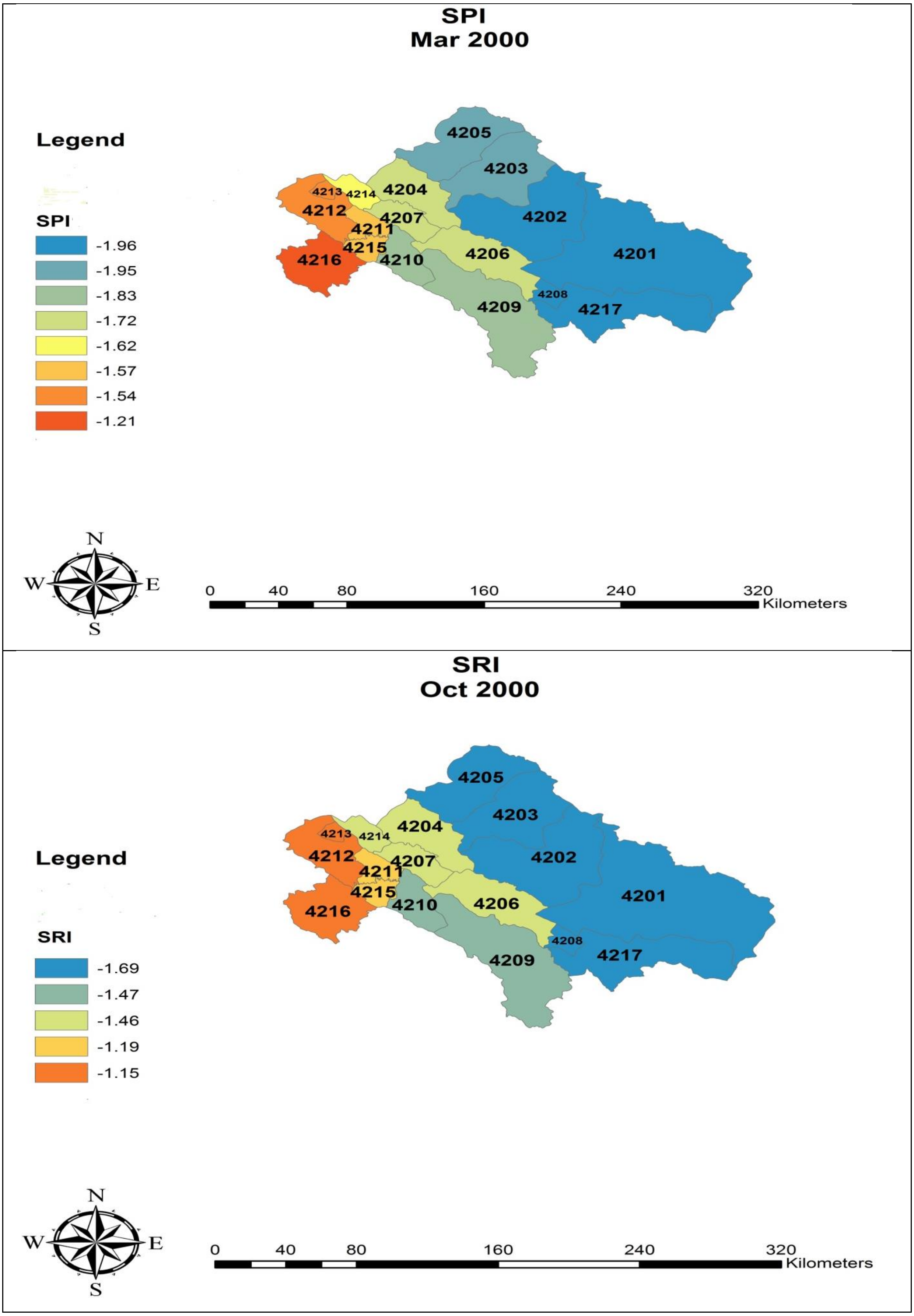


Figure 4.21: Spatial pattern of minimum drought indices during 2000 drought

The frequency of meteorological and hydrological drought of different durations at the stations is shown in Tables 4.18 and 4.19. As expected, the frequency of significant meteorological drought decreased with the increasing of its duration. The total frequency of meteorological and hydrological drought occurrence is nine at all sub-basins during 1971-2003. Unlike meteorological drought, the frequency of hydrological drought occurrences with durations of five and six months was more than other durations. The frequency of meteorological and hydrological drought is shown in Figures 4.22 to 4.25.

Table 4.18: Frequency of the most significant meteorological drought occurrences for each sub-basin

Sub-basin/month	1	2	3	4	5	6	7	8	9	10	11	12	Total
4201	-	4	-	5	-	-	-	-	-	-	-	-	9
4202	-	4	2	2	1	-	-	-	-	-	-	-	9
4203	-	4	3	2	-	-	-	-	-	-	-	-	9
4204	-	3	3	-	2	1	-	-	-	-	-	-	9
4205	-	1	3	1	1	-	2	1	-	-	-	-	9
4206	-	-	2	2	3	1	1	-	-	-	-	-	9
4207	-	-	3	2	3	-	1	-	-	-	-	-	9
4208	-	1	2	2	2	2	-	-	-	-	-	-	9
4209	-	1	2	2	2	2	-	-	-	-	-	-	9
4210	1	1	1	2	1	1	1	1	-	-	-	-	9
4211	-	1	4	3	-	-	1	-	-	-	-	-	9
4212	-	2	3	3	-	1	-	-	-	-	-	-	9
4213	-	2	3	-	3	1	-	-	-	-	-	-	9
4214	-	2	2	2	1	2	-	-	-	-	-	-	9
4215	-	4	2	1	1	1	-	-	-	-	-	-	9
4216	1	5	-	1	1	1	-	-	-	-	-	-	9
4217	-	1	-	4	2	2	-	-	-	-	-	-	9
Total	2	36	36	34	23	15	6	2	-	-	-	-	-

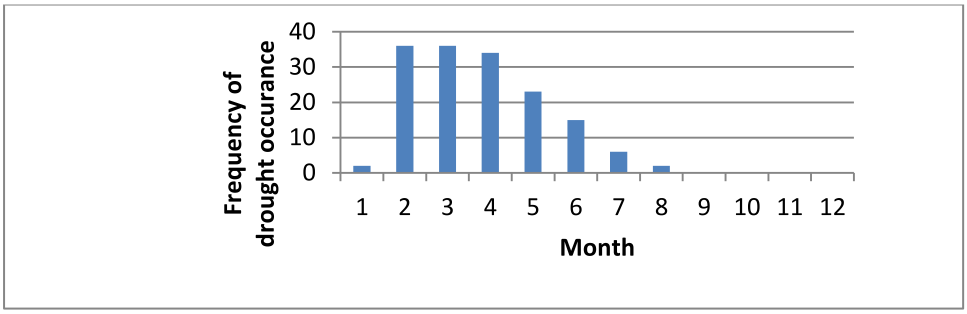


Figure 4.22: Frequency of meteorological drought occurrence in Zayandeh Rud basin

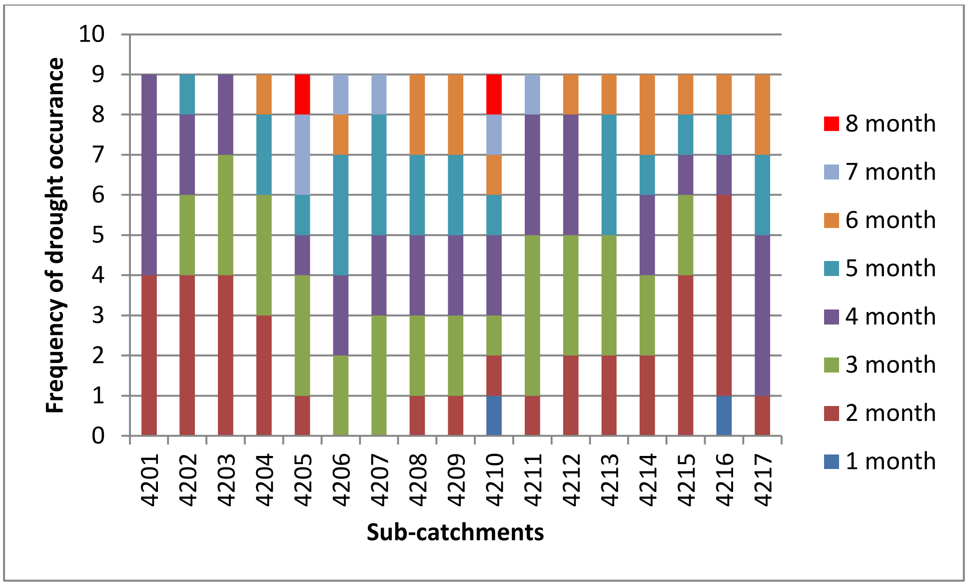


Figure 4.23: Frequency of meteorological drought occurrence in sub-catchments

Table 4.19: Frequency of the most significant hydrological drought occurrences for each sub-basin

Sub-basin/month	1	2	3	4	5	6	7	8	9	10	11	12	Total
4201	-	-	1	4	-	1	-	-	-	2	-	1	9
4202	-	-	2	1	2	2	-	2	-	-	-	-	9
4203	-	1	5	2	1	-	-	-	-	-	-	-	9
4204	-	1	2	-	1	2	3	-	-	-	-	-	9
4205	-	-	1	1	1	1	3	-	-	-	-	2	9
4206	-	-	-	-	2	4	-	-	-	-	1	2	9
4207	-	-	-	1	2	3	-	-	-	-	-	3	9
4208	-	-	-	-	2	3	1	1	-	-	1	1	9
4209	-	-	-	1	3	2	-	-	-	-	2	1	9
4210	-	-	-	1	4	-	1	-	-	-	1	2	9
4211	-	1	2	-	2	-	4	-	-	-	-	-	9
4212	-	-	1	1	2	2	1	2	-	-	-	-	9
4213	-	-	-	-	3	3	3	-	-	-	-	-	9
4214	-	-	-	2	-	5	1	1	-	-	-	-	9
4215	-	-	2	-	2	1	4	-	-	-	-	-	9
4216	-	-	-	-	2	3	2	1	-	-	1	-	9
4217	-	-	-	-	2	2	2	-	-	-	2	1	9
Total	-	3	16	14	31	34	25	7	-	2	8	13	-

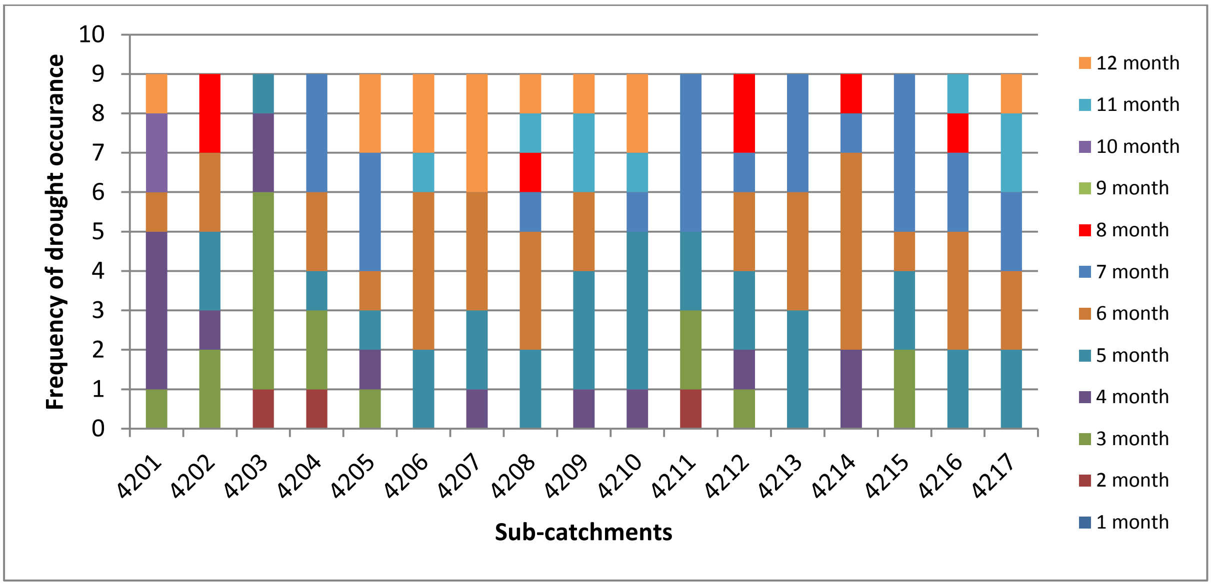


Figure 4.24: Frequency of hydrological drought occurrence in sub-catchments

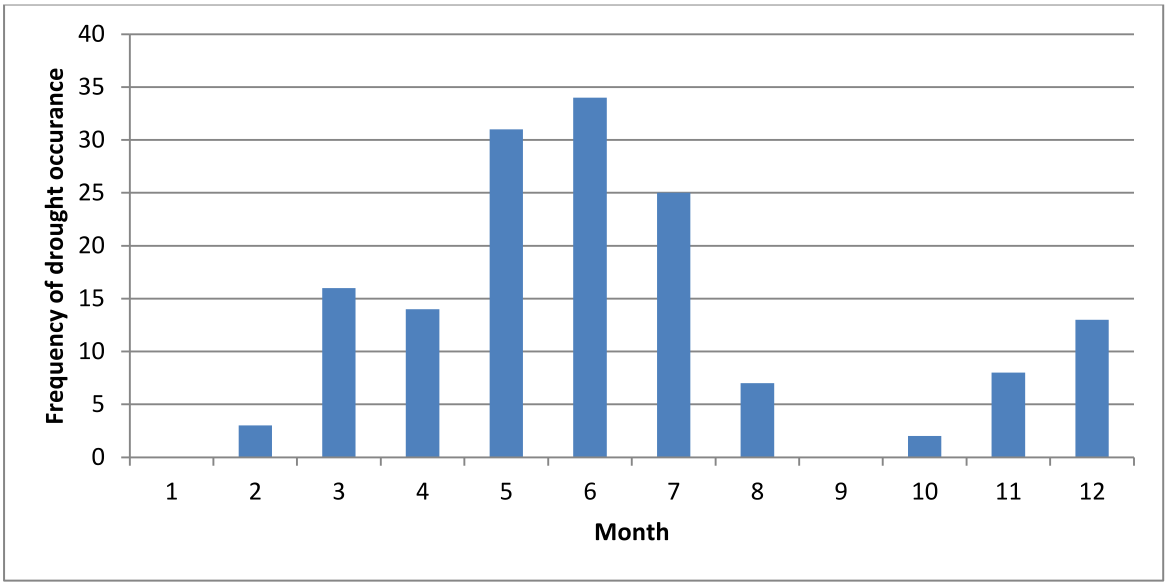


Figure 4.25: Frequency of hydrological drought occurrence in Zayandeh Rud basin

4.3.6 Comparison of indicators

Table 4.20 expresses the various indices for drought recognition for all the years in the historical sequences for the sub-basins. It shows that SPI and SRI determined different drought events during the last 30 years. The most severe drought in Figures 4.6, 4.7 and 4.8 started in January 1998 and lasted until December 2000. For all the driest years, the SPI indicates the drought onset at the same time or earlier than SRI indicates.

Even if there are some variations between the meteorological and hydrological droughts in the sub-basins, there are the same obviously expressed dry years recognized through both two indices too. During 1998-2001, there is a significant dry episod, the most intense drought in the previous 34 years. Throughout the equal episod, droughts happened over other parts of Iran, Asia, Europe, and the USA(Golian et al., 2014). The sea surface temperatures in this period in the eastern Pacific were cold, unlike the sea surface temperature in India and the western Pacific (Hoerling and Kumar, 2003). In the USA and Europe, many investigations concentrated on the effect of sea surface temperatures on droughts (Kiladis and Diaz, 1989, Barlow et al., 2002). Limited researches have referred this problem in Iran (Golian et al., 2014). The most severe drought of 1998-2000 in the Zayandeh Rud basin may have been caused by ENSO; which adjusts rainfall patterns crosswise the tropics and segments of the mid-latitudes. The average precipitation between 1998 to 2001 was 62-80% lower than the long-period climatology correspondingly (Darvishi A, 2008).

For analysing drought duration and severity, three events are studied and each consists of one decade. For each decade, the examination of the average quantities of SPI-12 and SRI-12 displayed that in the first episode (1971-1981) for all sub-basins the drought occurred in 1972, 1976 and 1980. For the second event (1982-1991) the drought occurred in 1984 and 1990. For the last event (1992-2001) the drought occurred in 1996, 1998, 1999 and 2000. So, Table 4.20 explainS the lowest value of indices for each decade and the sum of maximum duration for each decade.

The most significant drought is found in event 3; where the SPI indicated the most severe drought was from January 1996 until November 2000. The total duration for whole basin was about 17 months.

The record of hydrological drought recognized the most significant drought started from January 1996 until December 2000. The total duration for whole basin was about 31 months.

The meteorological and hydrological droughts happen at nearly the similar time or sometimes the SPI detects the drought onset between one and three months earlier than the SRI. Therefore, in some drought events streamflow reacts to rainfall deficit with some delay period; SPI probably is a beneficial indicator for drought initial beginning discovery. However, streamflow reveals less variability contrasted to rainfall and therefore, explains drought perseverance well. As shown in Table 4.20, the two indicators are for all sub-basins located in an arid region, and averagely droughts have shorter durations in event 2. According to prior findings in the USA(Golian et al., 2014) streamflow based drought indices react to meteorological drought with a lag of 2-3 months regularly. Nevertheless, the figures display that meteorological and hydrological droughts happen at the equal time nearly. It can be clarified through the Zayandeh Rud basin having an arid climate and the deficit of streamflow significantly depends on the deficit of precipitation.

Based on the table, the SPI and SRI are alike relatively with regard to the drought beginning in arid and extremely-arid areas. However, based on SRI, the drought period is lengthier than SPI normally(Golian et al., 2014).

Table 4.20: Characterisation of the most significant drought events in the sub-basins

SC	**Event 1**				**Event 2**			**Event 3**		
	Drought Index	Start month	Sum of duration	Min index	Start year	Sum of duration	Min index	Start year	Sum of duration	Min index
4201	SPI	Jan 72	10	-1.21	Jan 84	4	-1.36	Jan96	14	-1.44
	SRI	Jan 72	16	-0.65	Jan 84	7	-0.98	Jan96	36	-1.05
4202	SPI	Jan 72	10	-1.23	Jan 84	5	-1.36	Jan96	12	-1.44
	SRI	Jan 72	11	-0.65	Jan 84	8	-0.98	Jan96	26	-1.27
4203	SPI	Jan 72	9	-1.23	Jan 84	4	-1.36	Jan96	12	-1.44
	SRI	Jan 72	14	-0.53	Jan 84	5	-0.96	Jan96	13	-1.25
4204	SPI	Jan 72	7	-1.04	Jan 84	9	-1.11	Jan96	14	-1.30
	SRI	Jan 72	8	-0.35	Jan 84	12	-0.76	Jan96	26	-1.17
4205	SPI	Jan 72	10	-1.23	Jan 84	9	-1.36	Jan96	23	-1.30
	SRI	Jan 72	15	-0.53	Jan 84	13	-0.96	Jan96	35	-1.25
4206	SPI	Jan 72	12	-1.20	Jan 84	9	-1.2	Jan96	21	-1.36
	SRI	Jan 72	16	-0.65	Jan 84	12	-0.9	Jan96	41	-1.17
4207	SPI	Jan 72	10	-1	Jan 84	9	-1.2	Jan96	20	-1.36
	SRI	Jan 72	15	-0.49	Jan 84	12	-0.96	Jan96	40	-1.17
4208	SPI	Jan 72	10	-1.2	Jan 84	9	-1.34	Jan96	18	-1.45
	SRI	Jan 72	16	-0.65	Jan 84	13	-0.60	Jan96	41	-1.25
4209	SPI	Jan 72	11	-1.2	Jan 84	9	-1.16	Jan96	20	-1.36
	SRI	Jan 72	15	-0.65	Jan 84	12	-0.83	Jan96	38	-1.07
4210	SPI	Jan 72	11	-1.03	Jan 84	9	-1.14	Jan96	22	-1.30
	SRI	Jan 72	17	-0.49	Jan 84	10	-0.83	Jan96	39	-1.07
4211	SPI	Jan 72	8	-1	Jan 84	8	-1.13	Jan96	20	-1.22
	SRI	Jan 72	10	-0.42	Jan 84	12	-0.7	Jan96	24	-1
4212	SPI	Jan 72	7	-1.10	Jan 84	6	-1.13	Jan96	17	-1.17
	SRI	Jan 72	14	-0.2	Jan 84	9	-0.50	Jan96	29	-1
4213	SPI	Jan 72	11	-1.11	Jan 84	9	-1.13	Jan96	17	-1.17
	SRI	Jan 72	16	-0.35	Jan 84	12	-0.7	Jan96	26	-1
4214	SPI	Jan 72	9	-1.11	Jan 84	9	-1.11	Jan96	16	-1.17
	SRI	Jan 72	16	-0.35	Jan 84	12	-0.7	Jan96	25	-1.05
4215	SPI	Jan 72	6	-1	Jan 84	7	-1.06	Jan96	15	-1.17
	SRI	Jan 72	11	-0.41	Jan 84	12	-0.7	Jan96	27	-1
4216	SPI	Jan 72	9	-1.10	Jan 84	6	-1	Jan96	11	-1.13
	SRI	Jan 72	17	-0.2	Jan 84	12	-0.5	Jan96	32	-1
4217	SPI	Jan 72	10	1.18	Jan 84	9	-1.34	Jan96	23	-1.45
	SRI	Jan 72	16	-0.65	Jan 84	12	-0.98	Jan96	41	-1.25

4.3.7 Causes of drought

4.3.7.1 Large-scale climate

To recognize weather elements which effect drought, significant features of the cold phase

ENSO, La Nina, which directed to obstinately cold sea surface temperatures in the eastern Pacific and warm sea surface temperatures in the Indian and Western Pacific requires to contemplate. Subsequently, droughts happened in numerous area of the globe containing Iran. The ENSO phenomenon is one of the key leader of droughts and alters rainfall outlines over central Iran considerably (Golian et al., 2014). The most significant relationship is between two climate signals e.g. average of June-October SOI (as a predictor for ENSO) and total November-March streamflow. Also there is correlation between the average of December - March NAO and total April-July streamflow for the dry years 1972, 1976, 1980, 1984, 1990, 1996, 1998, 1999 and 2000 shown in Figure 4.26 (whish shows with red points). The results are extracted from previous research (Araghinejad et al., 2006) and plotted for the drought events in dry years. (Araghinejad et al., 2006) used a generalized linear model regression to forecast streamflow versus SOI and NAO. Low SOI and NAO are accompanied by reduced rainfall and river discharge in the Zayandeh Rud basin in dry years.

There is annual variable rainfall in the basin (Figure 4.1 in an appendix) and a dry period sometimes has a near normal number of days with measurable rain; but the rain is often more spotty and less intense than in wetter periods. The summer months typically have less precipitation than other months with the lowest average monthly precipitation in August and September. November to April are typically the wettest months. During the reference period, droughts have been more severe where the difference from warm season to cold season is the greatest.

Moreover, elevation has an important effect on climate specification of the basin. According to Dumbarton climate classification, most of the Zayandeh Rud basin is identified as semi-dry to ultra-dry climate and only a very small portion of the overhead basin fields lay in a cold climate. Except ENSO, precipitation of the basin is influenced significantly by Mediterranean rainfall systems, which enter north-west of the country.

The western mountains of the basin receive more rainfall. The annual precipitation ranges from 407.64 mm on the small upper portion of the basin to 105.42 mm near the Gavkhoni swamp.

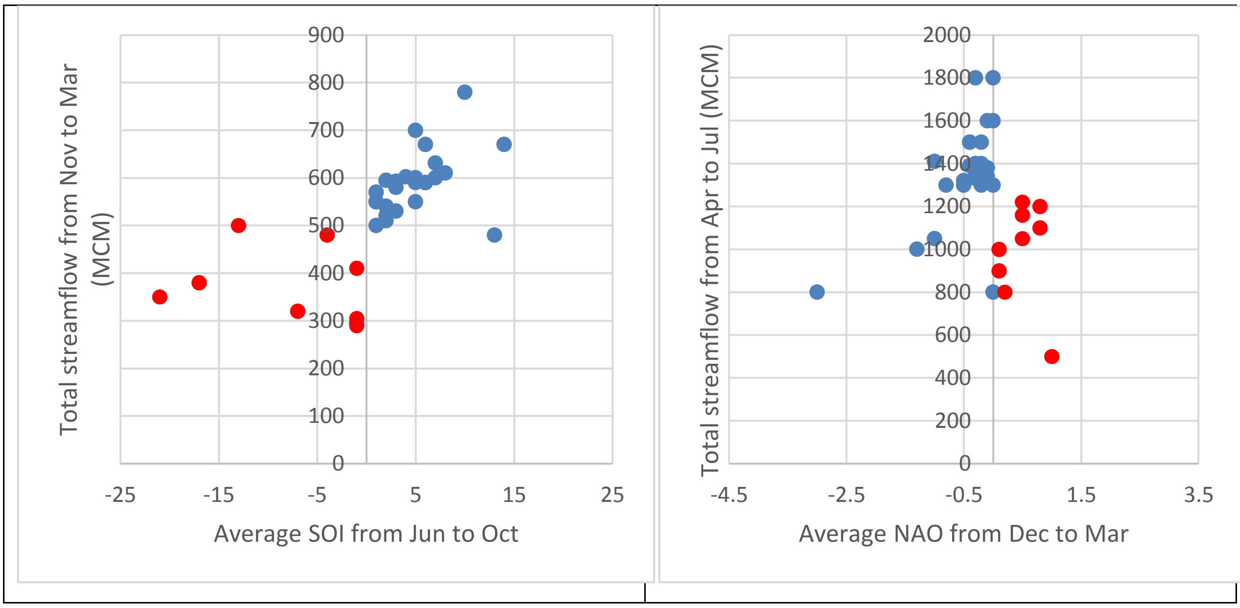


Figure 4.26: Variation of seasonal streamflow during 34 years (1971-2005) of Zayandeh Rud River with SOI and NAO. Red points show dry years and blue points show other years (include wet and normal years).

4.3.7.2 The basin climate

4.3.7.2.1 Role of temperature and evapotranspiration

Temperature has important role in drought intensity. Sometimes droughts are related with episodes of extreme heat, which can produces more evapotranspiration(Hossain et al., 2012).

Evapotranspiration (E-T) is the mixture of evaporation from the soil and transpiration from plants. Soils start to dry, and plants are influenced when the amount of E-T surpasses the amount of rainfall stock. There is a reaction impression that supports to extend the expansion of drought. When soils dry, water accessible for plants to transpire into the atmosphere is fewer. Throughout the growing season, in the Zayandeh Rud basin particularly, wheat and barley can contribute to atmospheric moisture considerably compared to rice and potato. When that reason of moisture is declined, moisture available for the growth of rainfall is fewer (Shukla et al., 2015). Figure 4.27 idicates both E-T and rainfall for an episode of four months throughout the growing season at the Zayandeh Rud basin. While the water balance (precipitation minus E-T) is negative, net drying occurs.

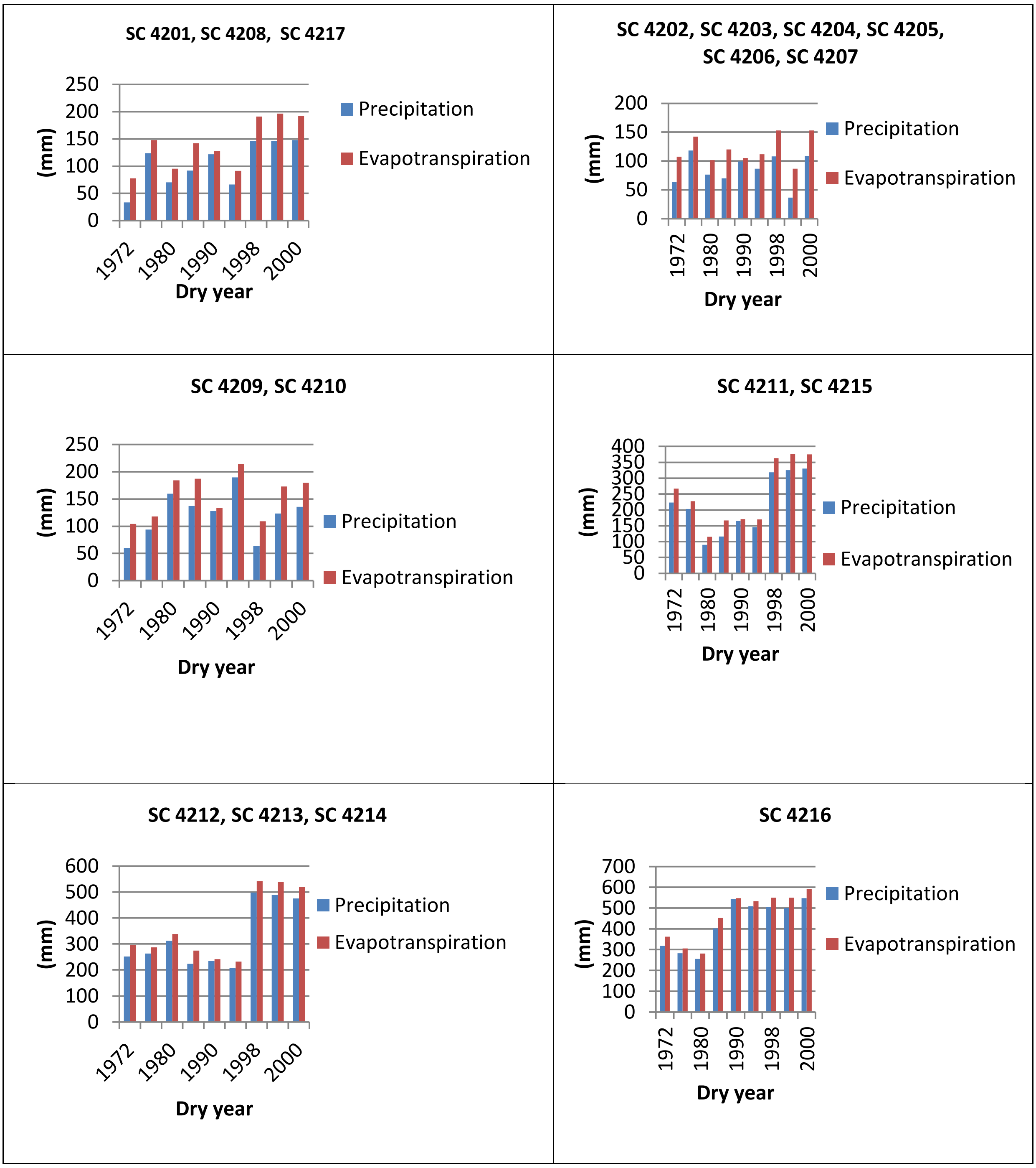


Figure 4.27: Compare precipitation and evapotranspiration in all sub-catchments

4.3.7.3 Human influences on water scarcity and drought

The underlying causes of most droughts can be related to changing weather patterns through the build-up of heat on the earth's surface; meteorological changes which result in reduced cloud cover; and a distribution of rainfall, that affects evaporation rates. Drought in the Zayandeh Rud basin is mainly caused by a lack of precipitation, especially during winter and spring. The first warm period can already lead to drought, including a risk for agriculture and hydrology. Due to climate change, drier winters and springs will occur more frequently in the Zayandeh Rud basin. The resultant effects of drought are aggravated by human activities such as poor irrigation and cropping methods, which reduce water retention of the soil; and improper soil conservation techniques that lead to soil degradation. The water emergencies in the basin result from more than just dry weather; droughts have a direct, human cause called demand-driven drought.

Industry development, population growth, and failing water supply systems play a significant role in creating water emergencies. If there is no balance between water demand and supply, even a few months of lower than normal precipitation is sufficient to trigger an emergency and drought. In the basin, more intensive land use practices create hydrological drought. Therefore, human activities to promote economic development create a demand for more water than is normally available.

4.3.7.3.1 Impact of development of water resources

Although the quantities of water resources have developed over the past 50 years, Zayandeh Rud remains vulnerable to drought. The progress of water resources' development from 1953 to 2020 is represented in Figure 4.28. The reason for this sustained risk is the consequence of three determinants. Firstly, planners appear to have used average conditions for planning purposes, meaning that there will be a shortfall once every two or three years (on average, and with a high probability of two or more continuous years below average). Secondly, both natural flows and trans-basin flows into the basin depend on winter and spring precipitation. When precipitation is below normal, flows in the Zayandeh Rud basin, and the trans-basin diversion tunnels are also below normal. As a result all the water resource developments cannot provide any significant insurance against a drier than normal winter and spring; as their capacity is only equal to the average annual flow of the Zayandeh Rud basin. Therefore, the graph for the driest years of 1972, 1976, 1980, 1984, 1990, 1996, 1998, 1999 and 2000 suggests more vulnerability to water scarcity than other years with little or no margin for coping with water shortages. The construction of new water resource developments that include the Chadegan Reservoir, and Kurang tunnel, cannot overcome this vulnerability to drought under current management practices. The third factor is that the extractive capacity of all users (Figure 4.29) is at or even above average. Experience confirms that in a short water basin, all available water is consumed as soon as it is made available (Molden 2001). This means that the basin has kept the same relative level of water scarcity over each phase of development. It is almost unavoidable this will again occur once the final phase of water resources' development is complete. The construction of new irrigation infrastructure in the basin raises extractive capacity. In periods of water stress, the surface systems can supplement groundwater. Supplying surface water to the irrigation systems will encourage farmers to enhance their irrigated area (Figure 4.30) and in water short periods when surface water supplies are deficient they will compensate their demand by groundwater pumping.

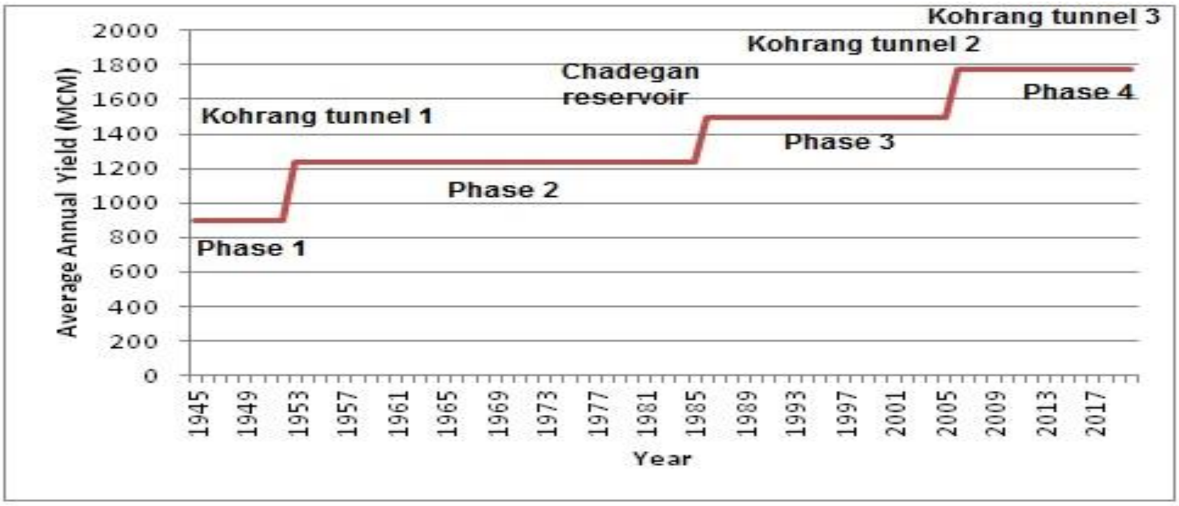


Figure 4.28: Average annual yield (MCM) by development water resources in the Zayandeh Rud basin

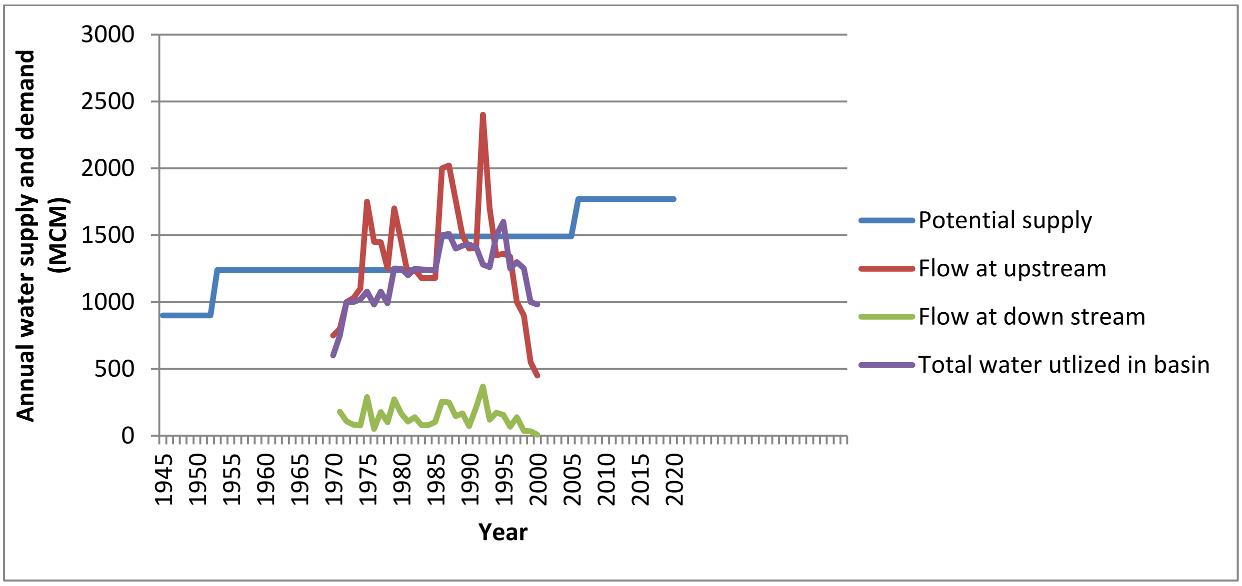


Figure 4.29: Comparison of average water supply and demand in the Zayandeh Rud basin

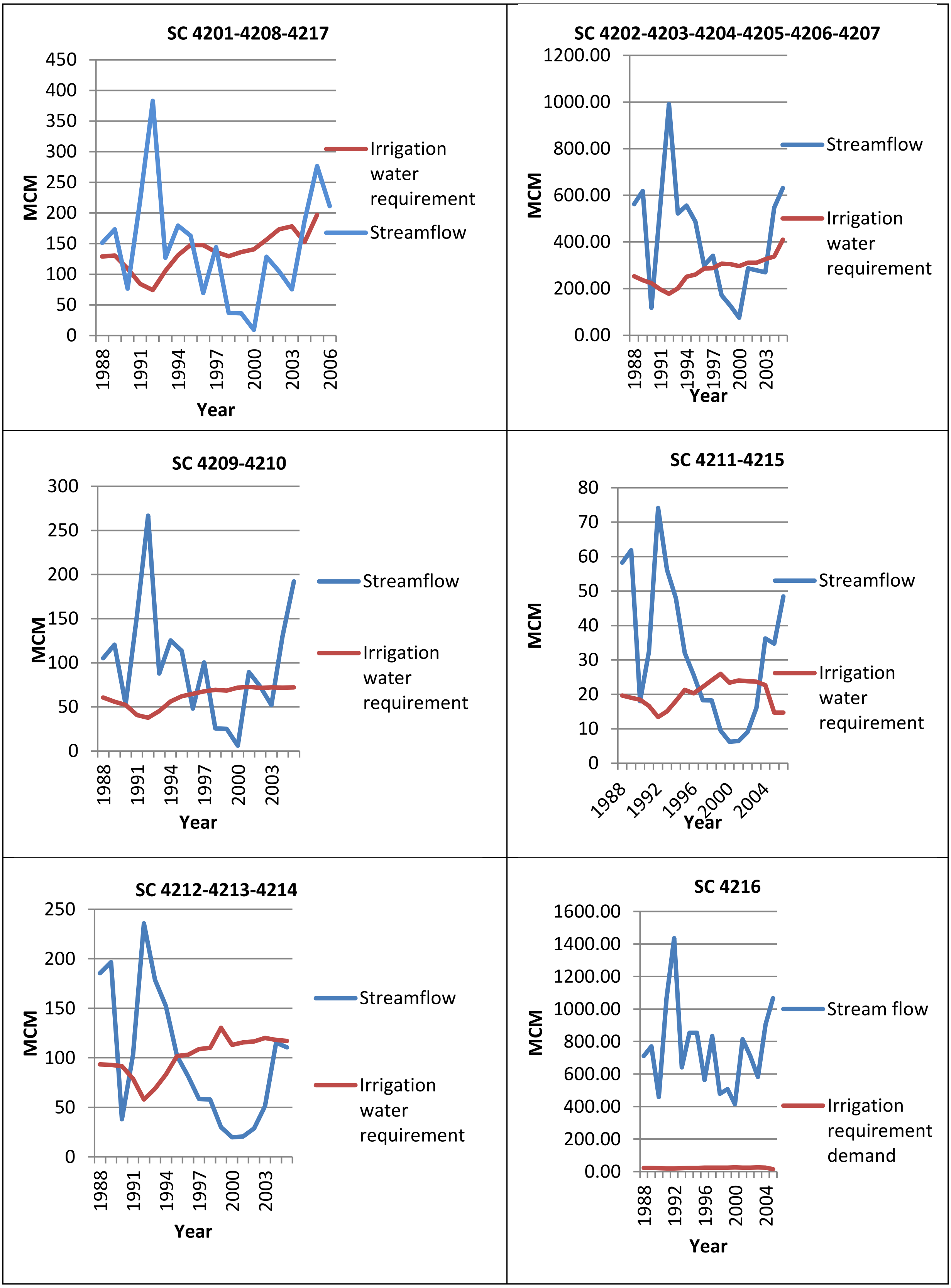


Figure 4.30: Comparison between stream flow and irrigation water requirement in each sub-catchments

4.3.7.3.2 Long-term changes in irrigated areas

Comparing irrigated areas shows that from 1988 to 2006 the irrigated area in all sub-basins increased, especially in recent dry years (1996, 1998, 1999 and 2000). Therefore, it can increase the vulnerability to hydrological drought because of reducing the flow of water by increasing drainage. The greatest increases in irrigated areas have occurred in sub-catchments 4202, 4203, 4204, 4205, 4206 and 4207. The results are shown in Figure 4.31.

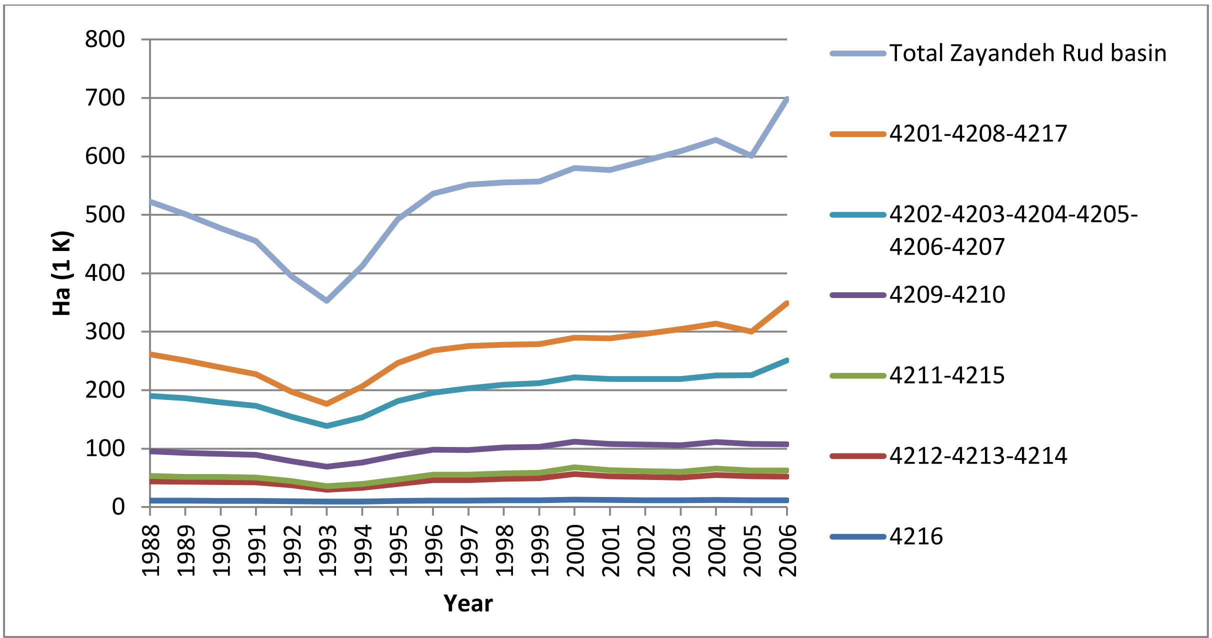


Figure 4.31: Increase irrigated area for each sub-catchment

4.3.7.3.3 Impact of low water use efficiency in irrigated crops

The water use efficiencies of all irrigation systems in the Zayandeh Rud basin are low, (Figure 4.32) averaging about 34%. In addition, the irrigation system has recorded one of the lowest efficiency grades in Iran during a dry cropping season. Moreover the irrigation system in the sub-catchments' upstream (4210, 4211, 4212, 4213, 4214, 4215 and 4216) has recorded lower water use efficiency (Table 4.20); as these sub-catchments are located at high elevation with a high slope. The high water use in this system is attributed to the following reasons.

The majority of the irrigated lands contain soil consisting of loam to clay loam. The seepage and percolation rates of these soils are about 0.4 to 0.8 inch per hour. These kinds of soils have much higher percolation rates than a saturated soil. Therefore, this may cause more damage during drought periods.

The major crops cultivated in this system are wheat and rice. Compared to other crops, rice has a high water requirement. Moreover, rice needs prior preparation of land. This process consists of initial land soaking (3-7 days) and ploughing, bund repair, puddling, and levelling twice

The initial soil moisture content, surface condition, soil type, level of weed infestation, losses during operations, length of irrigation canal and maintenance of standing water, all contribute to the overall water requirement in the land preparation process. To keep the standing water, the evaporation, seepage and percolation requirements must be met continuously. The water requirement rises with the growth of the duration of land preparation. The normal land preparation method needs a minimum of two weeks; whereas due to various causes like inadequate irrigation stores, farmer's negligence, lack of management practices, insufficient machinery etc. this cultivation period may last up to 35 days. According to (Hassan et al., 2007) an annual water saving of 9% could be reached by shortening the land preparation period.

The water supply to the Nekouabad and Abshar irrigation system located in sub-catchment 4206 measures about 200 MCM of water use during the land preparation. This is almost twice the amount of water necessitated by seepage, percolation and evaporation all together. It is evident that not only the climate variables or physical composition (permeable soil, high slopes, etc.) of the area handles scarcity of water; much water is lost due to poor management of the water supply during land preparation for rice.

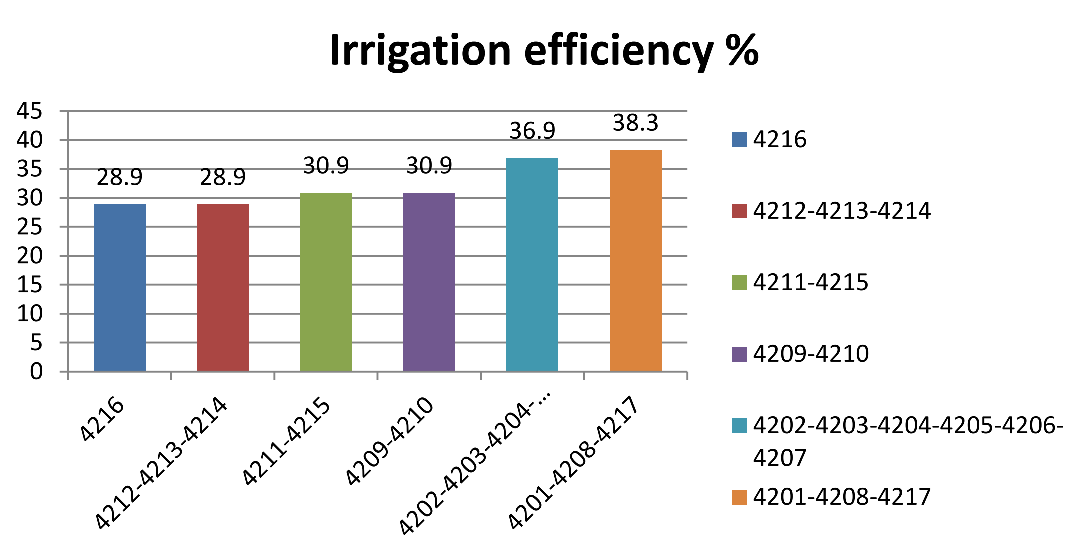


Figure 4.32: Irrigation efficiency in all sub-catchments

4.3.7.3.4 Mismatch of crops with soil type

The command area of irrigation systems consists of three major soil types: clay soil with lower infiltration rate (less than 0.2 inch per hour) in upstream sub-catchments (4210,4211,4212, 4213,4214, 4215 and 4216) and in sub-catchment 4206 in middle of the basin; the clay loam, and loam with moderate to high infiltration rate (0.2-0.8 inch per hour) in the rest of the basin. These kinds of soils have a much higher percolation rate than a saturated soil and also unlike clay soil take a shorter time to warm up and drain quickly and lose the water in spring and summer. However, all three kinds of soil have moderate to high permeability. The cultivation of rice in the moderate to high permeable soils has resulted in an extremely high water requirement in the Zayandeh Rud basin. Moreover, the land preparation requirement for growing rice is highly water intensive. At present, the agricultural management agencies of Zayandeh Rud are unable to rectify this issue due to their lack of control over the crop types cultivated by farmers.

A comparison of water demands for rice and other crop patterns under the present irrigation efficiencies was carried out (Figure 4.34). This calculation considers the irrigation water requirement by rice cultivated in highly drained soils. Also Ministry of Agriculture decided to apply 20% conversion from wheat to rice cropping from 1965 to 2000 (Figure 4.33), so water consumption and the risk of hydrological drought increased. Table 4.21 indicates the results of this estimation.

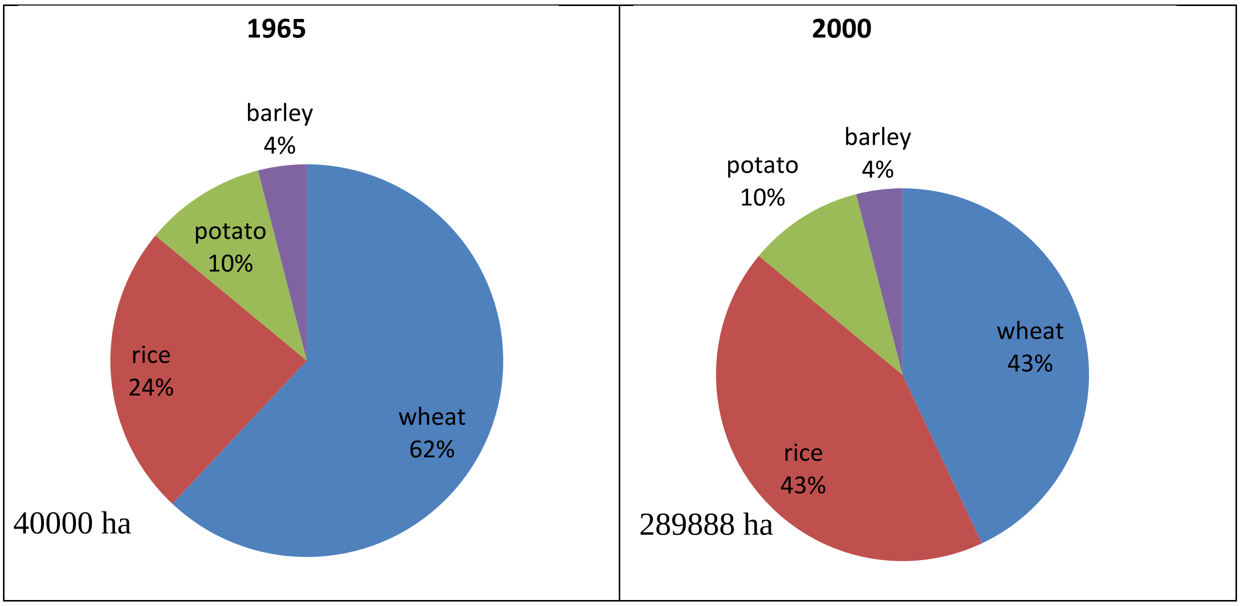


Figure 4.33: Changes in cropped area and cropping patterns between 1965 and 2000 in Zayandeh Rud basin (Esfahan regional water authority, 2012)

Table 4.21: Comparison crop evapotranspiration and irrigation requirement during high and low rainfall in the Zayandeh Rud basin.

	High rainfall	Low rainfall	High rainfall	Low rainfall	High rainfall	Low rainfall	High rainfall	Low rainfall
	Rice		Wheat		Potato		Barley	
Crop evapotranspiration(mm)	538	732	694	1005	180	232	184	238
Irrigation requirement (MCM)	88	199.35	61.66	142.53	7.64	18	20.31	50.10

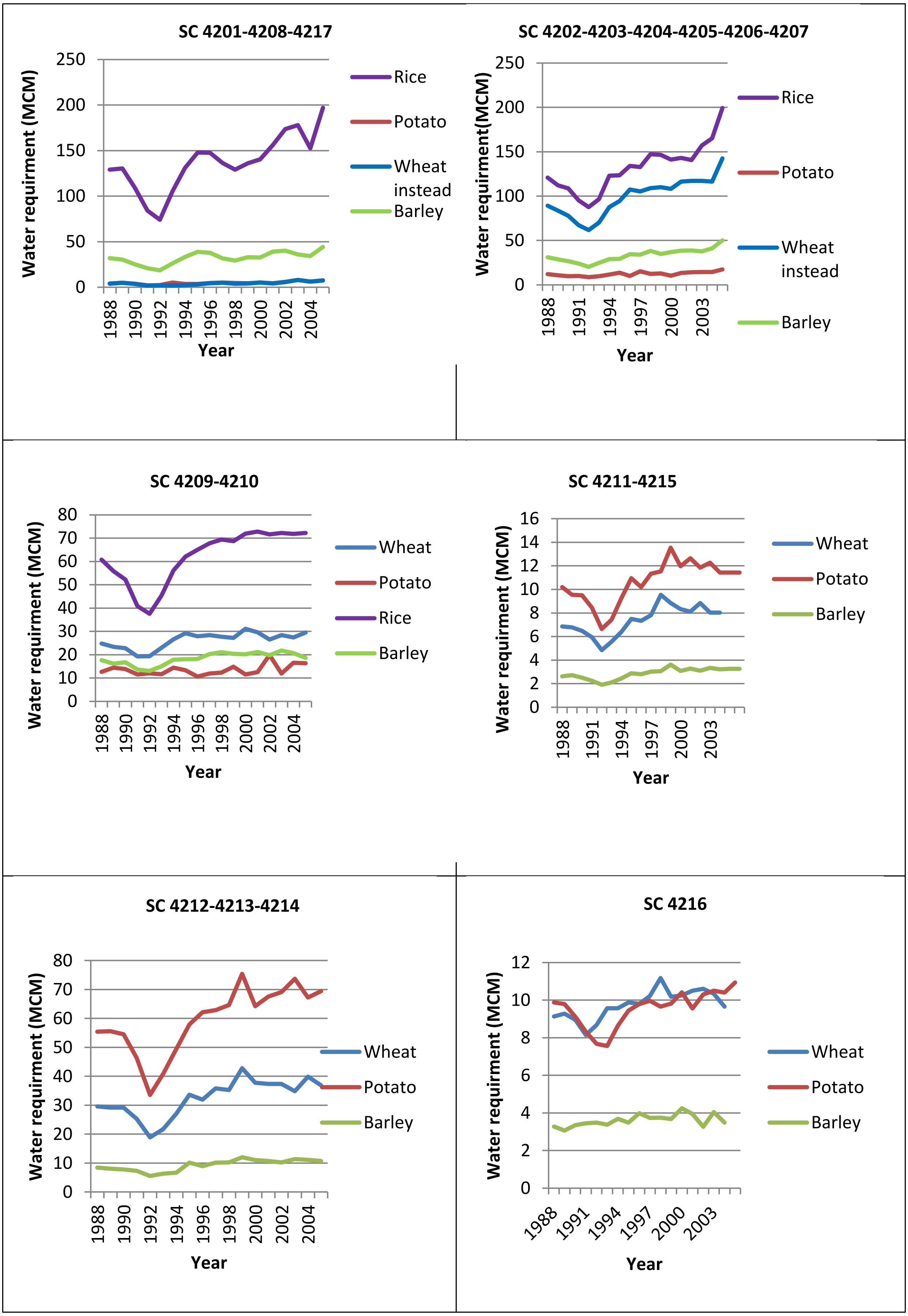


Figure 4.34: Water requirement for each crop in different sub-catchments

4.3.7.3.5 Impact of increased urban population and their demand

-Growth in domestic water demand

Population increased considerably in the Zayandeh Rud in the past 45 years. In the 1956 census, there were some 420,000 people in the basin; however, in 2000, the total population was 2,380,000, a increase rate of 5.9% per year. Figure 4.35 illustrates the population increase in the catchment since 1956, anticipated to 2020 with a 2% annual increase rate from 1996 forwards. The fastest increase happened among 1956 to 1986, averaging near to 7%(Molle et al., 2009). However, in the past 15 years the growth rate has decreased to 2-2.5% a year. It is expected the urban population will reach up to 3million by 2020. As shown in Figure 4.35 domestic water demand has increased proportionally to population growth; also allocation to the domestic sector is estimated and is indicated. Although there is a return flow to the river through wastewater, it is only 5% of the total supply per year. Therefore, extraction of water flow is increased and has more of an effect on hydrological drought in dry years. The increase in population and increase of urban areas means the soil and the urban vegetation no longer emit water vapour (through evaporation). This causes an increase of temperature and problems due to an increase in heat.

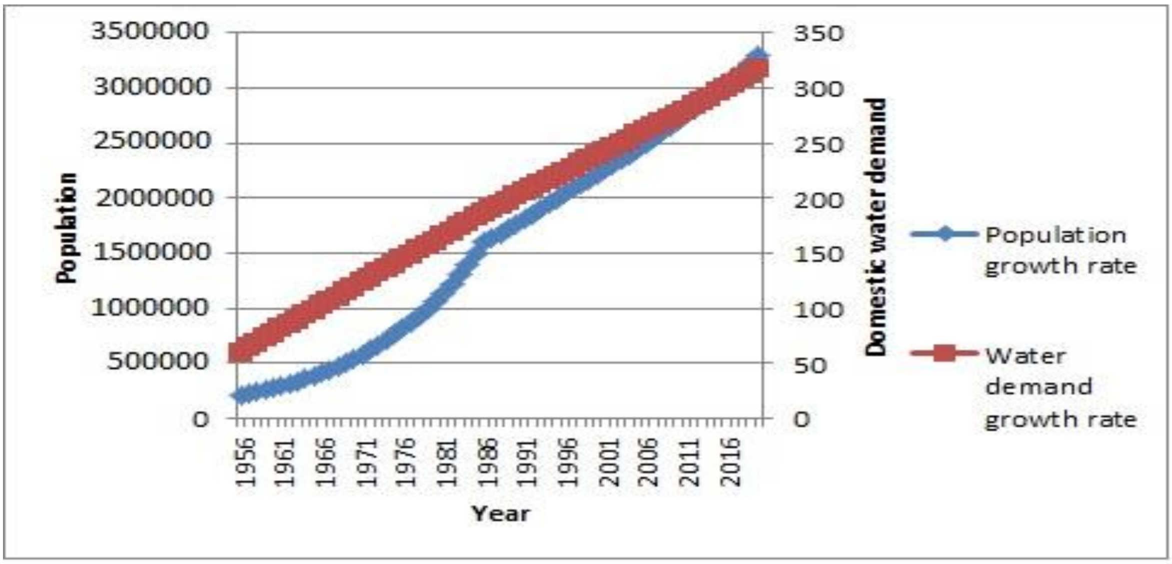


Figure 4.35: Population growth and increase domestic water demand

-Growth in industrial water demand

The Zayandeh Rud basin was selected by particular government policies in 1970 to rise industrial manufacture outside of Tehran. Esfahan was recognised as a main district, especially as the Chadegan Reservoir had just been finished, and it was expected water resources would be accessible easily. Four main industries (defence industries, Mubarak steel mill, Esfahan oil refinery and Sepahan cement factory) were improved from 1975 to 1977 (Molle et al., 2009), with a total annual demand of 60 MCM, which coincides with the drought year of 1976. In 1980, a polyacrylic factory was augmented with a requirment of 39 MCM. The growth of industrial demand for water is shown in Figure 4.36. In all the driest years, industrial developments have increased, as has industrial demand, which is one of the reasons for the hydrological drought.

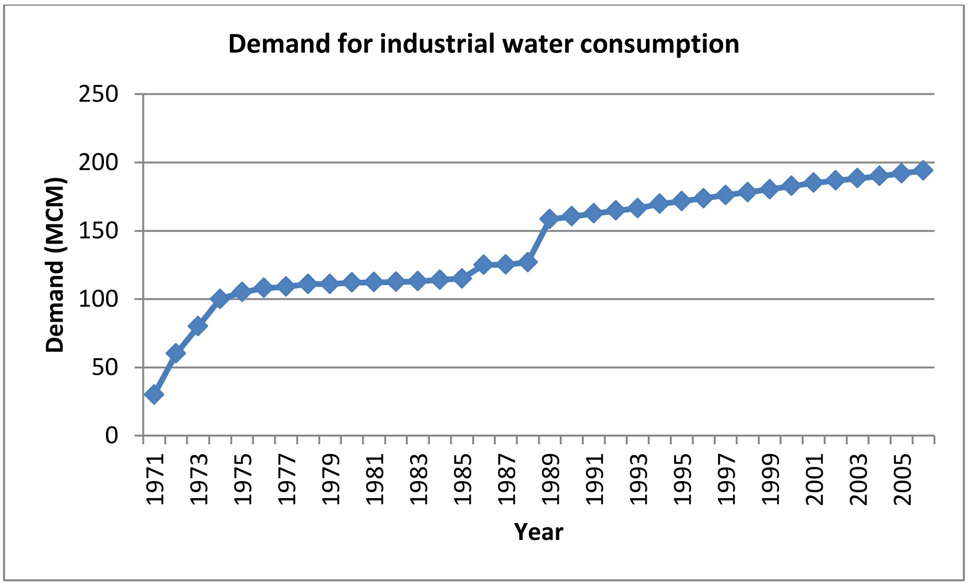


Figure 4.36: Industrial water demand in the Zayandeh Rud basin

4.4 Discussion

Many previous studies just focused on large scale drought characterization without consider effect of non-climatic factors. However, this study considered the effects of both climatic and non-climatic factors on drought characterization. In the studied drought events their trend and causes have been analysed (through the SPI and SRI drought indices) for 1971 to 2005 in the Zayandeh Rud basin. The SPI is a probability based index; therefore, calculating SPI using historic rainfall data can help to identify increased or decreased rainfall intensity periods. The advantage of using SPI is that it is standardized and it can classify drought intensity and it can help to present initial drought warning (Zargar et al., 2011). However, calculation of SPI considers only one climate variable, i.e., rainfall and not evapotranspiration or soil humidity, which are necessary factors in the hydrological process. To circumvent this limitation, in this research the SRI has been used to estimate hydrological drought. One important advantage of the SRI is its ability to help estimate hydrological/water resource drought for a large series of different time periods (Joetzjer et al., 2013). Analysis of SRI is based on a statistically computed standardized amount of streamflow over larger time periods of measured stream flow data, hence making it better to time series of raw streamflow data. Because raw data can not show the number of standard deviation below the mean and only with calculating Z score and standardize (by SRI), it is possible to analyze the number. Analysis of SRI is simple, negative values of SRI indicate lower than normal streamflow, and positive values indicate higher than normal streamflow. Moreover, spatial and temporal resolution can be achieved due to the standardisation of the index and daily updating. Even data from newly installed stream gauges can be used for hydrological drought characterisation because of interpolation abilities. However, SRI needs raw data to be transformed to fit a normal distribution curve which can be a challenge, specifically for low-flow episodes and short accumulation time periods. Unlike SPI, SRI fitted to normal distribution better because the number of zero streamflow is less compare to number of zero precipitation. Furthermore, appropriate gauge records to estimate the SRI is available sparingly because generally stream flow data is affected by upstream reservoirs. Most of previous study such as W.Buytaert and B. De Bièvre (2012) only calculate low flow for specific time period and did not classify hydrological drought intensity or used very broad classification (such as Falkenmark water stress classification). Also SRI can classify the intensity of the hydrological drought well.

Previous study (e.g. Akbari et al. (2015)) did not consider actual timing and duration of drought propagation, but this study analysed the drought propogation. For all significant drought events, the meteorological and hydrological droughts occur at approximately the same time or occasionally the SPI detects the drought onset between one and two months earlier than the SRI. Therefore, in some drought events streamflow responds to precipitation deficit with some lag time. The SPI may be a better indicator for early detection. However, this study found that streamflow shows less variability compared to precipitation and therefore better describes drought persistence. Basically in arid and hyper-arid regions such as the Zayandeh Rud basin, the SPI and SRI are quite similar with respect to the drought onset. However, drought duration based on the SRI is typically longer than the SPI. The basin has high permeable soil and because of the ground water system and water supply developments, the hydrological drought's intensity is smaller than meteorological drought. This study also found that SRI is able to reproduce the transformation of meteorological drought into hydrological drought. The majority of the drought events for most of the sub-basin were found in 1972-1973, 1976-1977, 1980-1981, 1984-1985, 1990-1991, 1996-1997, 1997-1998, 1998-1999, 1999-2000, 2000-2001, which are shown in Figures 4.6, 4.7 and 4.8. All stations experienced drought similarity for the reference period. Extreme drought is common in the Zayandeh rud basin (See Figure 4.9, 4.10 and 4.11). All of the rivers of the study region faced at least one-month's severe drought during recent decades especially during 1998 and 2001. The spatial characterization of the droughts were analysed in this study (Figure 4.13 to 4.21). The most significant meteorological and hydrological drought can be identified at sub-basins located downstream and in the west part of the Zayandeh Rud basin. This probably due to their smaller water storage capacity. Analyses of the drought trend by a Mann-Kendall test (Table 4.6) shows there is a significant drying trend at 95% for annual meteorological and hydrological droughts in sub-basins 4201, 4202, 4203, 4204, 4205, 4206, 4207, 4208, 4209, 4217. This drought trend is due to the decreasing trend in the rainfall downstream and west of the Zayandeh Rud basin. The average precipitations are higher in the stations located in the upper sections of the Zayandeh Rud river. In the mountainous area upstream of the river average precipitation is higher in the sub basins 4210, 4211, 4212, 4213, 4214, 4215 and 4216. There is also a slight trend of variability coefficients of average precipitation values from the top to the end of the river. In all stations, the significant meteorological drought trend was found in winter and spring. However, the significant hydrological drought was detected in autumn and summer. Moreover the spatial distribution of drought indicated and confirmed that the most significant extreme drought occurred in 1972 (of 2 to 5 months), 1998, 1999 and 2000 (2 to 12 months). The driest month for meteorological drought for each year was January, June, January and March respectively. Unlike the meteorological drought, the driest months for hydrological drought for the same years were July, October, October, October.

The most significant severe drought occurred in 1976 (of 2 to 6 months), 1980 (of 2 to 7 months) and 1996 (of 1 to 8 months). The driest months for meteorological drought for those years were April, January and February and for hydrological drought were July, August and September.

Moreover, moderate drought occurred in 1990. The driest months for meteorological and hydrological drought for this year were February and April with a duration of 2 to 7 months.

Analysing the frequency of the significant meteorological drought, the study found the occurrence of drought decreased with increasing duration. Meteorological drought was most likely for 2-3 months, while hydrological drought lasted 5-6 months.

Drought can have different causes. This research categorizes the causes by three factors: climate change, weather factors and human factors.

For the climate factor: two climate signals, ENSO and NAO can influence climate variation, rainfall and streamflow of the rivers in the basin. According to Grove (1998) and Shahab Araghinejad et al. (2006) there is a connection between fluctuations in the Southern Oscillation Index (SOI as a predictor of ENSO) and rainfall in Iran. This study found that in the Zayandeh Rud basin low SOI and high NAO are accompanied by reduced river discharge in the basin in dry years.

For the weather factors: decreasing precipitation caused by increasing temperature and evapotranspiration can raise the risk of both meteorological and hydrological drought.

For human factors: unlike Guadiana catchment (Van Loon & Van lanen - 2013), in the Zayandeh Rud basin the influence of climate and weather factors on meteorological and hydrological droughts is more significant compared to the effect of human activities such as land use.

However, human influences cannot be neglected. Some human impact on water scarcity and drought especially hydrological drought are shown below. In this study, it is assumed that precipitation does not change due to human factors in small scale (Moor & Dolman, 2003).

The results of the Zayandeh Rud basin confirm previous findings in other regions, e.g. Ding man, (2002) for China and Rowe et al. (1997) for U.S. that found expanded water use by domestic, industrial and especially extended irrigated areas mostly leads to lower average and dry season streamflow (Figure 4.29 and 4.30) implying a higher risk of drought. The reason is that more area under cultivation consumes more water by evapotranspiration. It causes low flow availability and makes hydrological drought longer and more frequent than meteorological drought. Also low irrigation efficiency, poor methods of irrigation, land preparation requirements, especially for rice that is cultivated more, and high transpiration losses result in a longer period of hydrological drought (see section 4.3.7.3). In the Walla basin in Sri Lanka (Neelanga Weragala, 2010) hydrological drought lasted 8 to 31% longer by increasing the area under cultivation.

From 1953 in the Zayandeh Rud basin, water supply systems were replaced by artificial infrastructures to keep pace with population growth. Surface runoff flows more quickly to the stream. Therefore, the basin quickly responds to precipitation. However, these water resources with the lack of management and without any additional measure lead to hydrological drought and are designed for a 5 year averages under normal condition of flow not for low flow. Therefore, during significant dry years which coincide with lower water availability in storage, greater water use causes hydrological drought. This implies that severity of hydrological drought is equal or smaller than meteorological drought, but the duration is longer.

The results of this research confirm the previous study in reservoir construction in Burkina Faso (Andreini et al., 2002): the new reservoirs may alleviate streamflow drought if water that was stored during the wet period is released during the dry period. However, when surface water is stored for irrigating crops during the dry season, there is an increasing demand which can result in hydrological drought which could last longer than meteorological drought.

New reservoirs in the Zayandeh Rud basin may decrease low flow in normal conditions, but in dry years cannot compensate for the risk of hydrological drought. For example, even with construction a new water resource (Kohrang tunnel 2), the basin exprinced significant drought between 1980 and 2002 (see figure 4.29).

4.5 Conclusion

Before analysing drought impacts on water accessibility and water requirements, holistic drought characterisation is essential (Nazemi et al., 2013). This chapter quantified the trends and features of meteorological and hydrological drought by utilising the SPI and SRI by (trend analysis, frequency and duration of drought) in the Zayandeh Rud basin for the period 1971-2005.Additionally, the effect of anthropogenic uses of water on drought characterisation is considered. The results are summarized as follows:

- The results prove the null hypothesis of no upward trend in drought in the upstream of the western part of Zayandeh Rud at significance level 95%. However, 10 out of the 17 analysed sub-basins of the central and downstream sub-basins showed an upward trend of drought
- At least one significant drought was detected in all sub-basins throughout the study episode, and the most extreme meteorological droughts appeared in the winter and spring months. The lengthiest period of the severest meteorological droughts was in the year 2000 and was 2 to 8 months, and the longest hydrological droughts was 7 to 12 months.
- The analysis of SPI-12 and SRI-12 indicates that the frequency of droughtdecreased with increase in its duration. The total frequency of meteorological and hydrological droughts is nine at all sub-basins during the period of 1971-2003. Meteorological drought occurrences lasting 2 to 3 months were more frequent whereas hydrological drought occurred more frequently for the time span of 5-6 months. Analyses revealed that the basin suffered from a range of moderate to extreme droughts during the study period. The driest years in the basin were 1972, 1976, 1980, 1984, 1990, 1996, 1998, 1999 and 2000. The most severe drought with long duration occurred

between 1998 and 2000 (see Table 4.15 to 4.17). This drought lasted almost 36 months without being interrupted by occasional wet spells. The drought could be due to the ENSO and La Nina events which changes sea surface temperaturs in the eastern Pacific and the Indian and western Pacific Ocean "(Golian et al., 2014) and Iran's geophysical location makes it vulnerable to these temporal though periodic weather events. It was found that the average temperature increased and average rainfall declined over this period. Also the catchment characterisation causes fast responding flowpath. Thus, meteorological drought impacts are enhanced in hydrological drought impacts. The typical Mediterranean hydrological regime that is manifested as a wet condition 6 months of the hydrological year and a mostly dry period after that, also contributes.

- In the basin, rainfall monitoring helped to predict drought , whereas stream flow data helped to establish the drought period. For all the driest years in all the sub- basins analysed in this study, the SPI showed an earlier or simultaneous onset with the SRI. As explained by Golian et al. (2014), this happens because after each rainfall episode in arid and extreme-arid regions , soil moisture evaporates very quickly and causes a decrease in streamflow (Golian et al., 2014). Usually in such regions, soil moisture levels are too small, and meteorological and hydrological droughts appear atsimilar times. However, it was found that hydrological droughts continued for a longer time.
- This chapter presented the importance of of human influence on drought. The construction of reservoirs with no sufficient surface water control or no measure of proper storage regulation in dry conditions, leads to more water demand and thus does not decrease the risk of hydrological drought. Drought

conditions, together with the increasing demands of water for domestic, industrial and agriculture uses and higher evapotranspiration losses leads to fluctuations in streamflow. In addition, the flooding method of irrigation causes the duration of hydrological drought to be longer compared to meteorological drought in the basin. In general, hydrological drought not only depends on duration of dry days, but it depends on duration and amounts of water consumption and also relates to catchment features (e.g. geology, land use and elevation).

CHAPTER FIVE: LINKING DROUGHT, WATER RESOURCES AND DEMANDS: IMPACTS AND RESPONSES AS SIMULATED BY A WATER MANAGEMENT MODEL

5.1 Introduction

Different studies analysed the severity of meteorological or hydrological droughts (Soulé and Yin, 1995), (Tallaksen and Hisdal, 1997), (Hisdal and Tallaksen, 2003), (Fleig et al., 2006). It is important to know that hydrological drought cannot only be generated by meteorological drought or climatic factors. Anthropogenic factors may affect it, and vice versa.

Water resources' droughts can happen where the demand for water outstrips supply due to both drought conditions and human activities.

Recently different large-scale studies have been done to examine drought at global or continental scale (Andreadis et al., 2005, Sheffield and Wood, 2008, Van Lanen et al., 2013). In these studies, droughts were derived from time-series simulated with large scale models, usually tested against documented sources or river flow data. All these investigations deal with a large amount of data (gridded data or data from numerous flow gauges) without measuring drought impacts. However, often the necessary data on catchment attributes and catchment conditions on a small scale are not available. Such data would make a hydro-water allocation model and investigation of underlying drought impacts and controlling mechanisms in spatial and temporal patterns significant. In addition, a model that measures drought impacts across a cascade of various levels from available water resources to water demands and socio-economic systems is missed in previous studies. A model in small scale for a specific area can help to identify the relative mitigation management in a similar area and then develop mitigation planning in the world, especially in catastrophic events such as drought.

Time to implement the management actions is a necessary factor of any drought management plan. Management plans should rely on meteorological, hydrological and agricultural indicators. An essential feature is for the indicators to be linked to drought management strategies and policies, which is not easy to do (Wilhite, 2000) (Iglesias and Moneo, 2005).

To determine the drought management strategy, current control measures, risk evaluation, an organisation of decision-making processes and measurement of possible mitigation plans are necessary. Especially in developing countries in arid and semi-arid areas, with the objective of making the plan to adapt the effect of future droughts, the selection of the appropriate moment to begin acting against drought is essential.

Usually, it is not economically efficient for all demands in a system to satisfy at 100%. However, the acceptable risk level, especially in a critical condition such as drought, is conditioned by available water resources and infrastructures and related to the characteristics and their flexibility (MARTIN-CARRASCO and GARROTE, 2007). Therefore, the risk analysis may consider the following aspects:

- Probability or severity of failures event
- Failure duration
- Economic impact of failures

It can be concluded that a water allocation model can solve the problem, especially during drought periods to design allocation schedules that satisfy the sustainability of water resources, economic efficiency and equity among waters and environmental flow requirements.

A water allocation model such as the WEAP model, can incorporate an integrated approach to water resource management. A WEAP model provides easy access to the catchment data.

Visualising and analysing the data can be done by applying simple spreadsheets, or GIS layers constructed in models. The model integrates simulation of both the natural and engineered elements of a water resource system by placing demand side problems: for example, water consumption patterns, equipment efficiency, re-use strategies, cost and water allocation schemes on an equal footing with supply-side resources such as available surface and groundwater, reservoir storage and inter-basin transfers. It gives the water manager a broad view of the consequences of several decisions on the system. Thus, because of the multi-faceted nature of the WEAP model, policymakers and water managers can understand "what if" scenario analyses by simultaneously taking account of an individual or a combination of causative factors. For example, significant climate change may cause drought, land use change, population and demand growth on the hydrology and economic relationships within the system. It can generate a complex reaction of the water resource system to these factors.

This chapter evaluates flow reduction in water supplies during reference and drought scenarios, and calculates unmet demands to evaluate the reliability of the system to cover the water demands. The objectives are:

- To examine the impacts of droughts on water supply and the water users and also human impact on flow reductions.
- To assess the socio-economic impacts of drought on agriculture in the basin.
- To test the ability of the existing drought management framework to manage severe droughts.
- To define the drought management strategies and evaluate the reliability of the system during drought periods.

This chapter is divided into six sections: the methodology is explained in section 2. The sensitivity and calibration of the Water Evaluation and Planning model (WEAP), to make different scenarios to evaluate impacts of drought on water resources and water demands are defined in this section. Section 3 describes the data sets for the model. Sections 4 and 5 are followed by results and a discussion on the parameters that are used for the sensitivity and calibration of the model. In addition, supply and demands are evaluated and analysed under different scenarios. Furthermore, the reliability of the water resources and water demand system under normal and drought conditions is determined. The benefits and weaknesses of the model are discussed in the discussion section, and drought management strategies and the socio-economic impacts are compared with other studies. The last section contains a summary and conclusion.

5.2 Methods: model and data requirement

A water management model for the Zayandeh Rud basin was constructed using the WEAP21 toolbox to assess the drought impacts, to estimate the reliability of the system throughout drought episodes and to suggest possible management options for the basin. The WEAP21 model can help to simulate various water related parameters, (precipitation, runoff, water quality, etc.) for both natural systems such as, rivers and ground water, and man-made structures (e.g. reservoirs). The required input data for model specification was collected from Esfahan Regional Water Authority, Iran Water Resources Authority and Iran Meteorological Institution. The geospatial details were also combined to examine the linkage between geophysical characteristics and management options.

The steps followed in this study to use WEAP are in accordance with the approach suggested by the developers of the tool (Sieber and Purkey, 2011). The steps are outlined below:

1. the study area, time period of study and the problem of study was formulated.
2. The ‘current account’ was established which consisted of average water demands from the three sectors – industrial, domestic and agricultural, water availability

(MUGATSIA, 2010) in the basin to arrive at the water mass-balance of the region which is the basis for the WEAP model.

3. Water supply and demand for dry years were estimated to develop the drought scenario.
4. Finally, evaluation was done to assess demand satisfaction for various sectors. Drought influences on the water control systems is examined through a scenario formation which has been set up to include the drought happening under present climate and under future climate change, which will be explained in the next chapter.

5.2.1 Model description

The WEAP s' system works on the simple approach of of water mass balance. The equation for the generic water balance is:

$$I_p + I_r + - O_{inf} - O_{irr} - O_e - O_{ab} - O_{out} = +/- \Delta S$$

Where Ip = precipitation, I_r = river inflows, O_{inf} = infiltration/percolation Oirr = irrigation demand, Oe = evaporation, Oab = domestic/industrial abstraction, Oout = outflows/spillage and The system performance depends on stock resources (e.g. rivers, groundwater, storages) of water transfers (extraction, transportation) and water requirements.

ΔS = change in storage.

The rainfall runoff method was applied to simulate stream flow in this study. This was constrained by the type of data available (rainfall, evaporation and crop data). The data which are necessary to perform rainfall-runoff simulation include:

1) Climate (precipitation and ET0)
2) Land use (area, Kc, effective precipitation)

Monthly stream flow data was modelled and compared to the natural stream flow provided by the Esfahan Regional Water Authority for this study. It was done because in this basin measured flow records from gauging stations are influenced by human water abstraction and do not show the flow originally from the rainfall-runoff process and also data for natural streamflow is available only for three stations (not for all 17 gauaging stations) so simulation for all the stations is necessary. The model was calibrated from 1997 to 2003. Also historical variations in demand were measured for all the water-use sectors and the WEAP was used as a water allocation model to simulate water demand in the catchment.

The following type of data is required to perform water allocation simulation (Table 5.1).

Table 5.1: Data required for water allocation model of WEAP

Type of data		Source or formula used	Data format	Time period
Supply and resources data	**River:** Streamflow relative to gauge	Data	ASCII data file format	1971-2005
	Groundwater: -Initial storage	Data	ASCII data file format	1971-2005
	-Hydraulic conductivity			
	-Specific yield:			
	-Natural recharge (%): inflows to the groundwater source by rainfall.			
	-Storage at river level (mm3):			
	Overflow	There is no overflow for this basin		
	Reservoir: Storage volume, storage elevation, height of reservoir, top of inactive, top of conservation and net evaporation of the reservoir	Data (See Table 5.3)		1971-2005

Table 5.1: Countinued

	Transmission link from supply to demand	Data	ASCII data file format	1971-2005
Catchment data	Observed precipitation	Data	ASCII data file format	1971-2005
	Effective precipitatio	Formula (See equation 3 and 4 in appendix)	ASCII data file format	1971-2005
	ET Potential and ET real	Formula (See equation 1 and 2 in appendix)	ASCII data file format	1971-2005
	Area	Data (calculated by GIS)	Vector format (shapefile)	1971-2005
	Infiltration/runoff flow (%)	Data and assumptions	ASCII data file format	1971-2005
Demand data	Irrigation demand	Formula (See equation 5 in appendix)	ASCII data file format	1971-2005
	Domestic and industrial demand	Data (Lit per person or per unit)	ASCII data file format	1971-2005
	Irrigation return flow	Return flow=inflow*(1-consumption)	ASCII data file format	1971-2005

5.2.2. Model operating rules

The Zayandeh Rud basin was divided into 21 sub-basins (Figure 5.1). However, the data available for 17 sub-basins is referred in the following as the WEAP sub-basins (4201 to 4217). There are several reasons for this subdivision:

1) Rainfall data, which are the primary input for the model, are available for 17 rainfall zones. Therefore, sub-basins of the model had to include these rainfall zones.
2) Most of the data needed to run the water allocation model were available at this basin level.
3) Some of these sub-basins have a gauging station at their outlet that was applied for comparison with the simulated flow for the calibration.

The model, as it is applied in this study, operates on a monthly time-step. The period of study was from 1971 to 2005, when the necessary data was available.

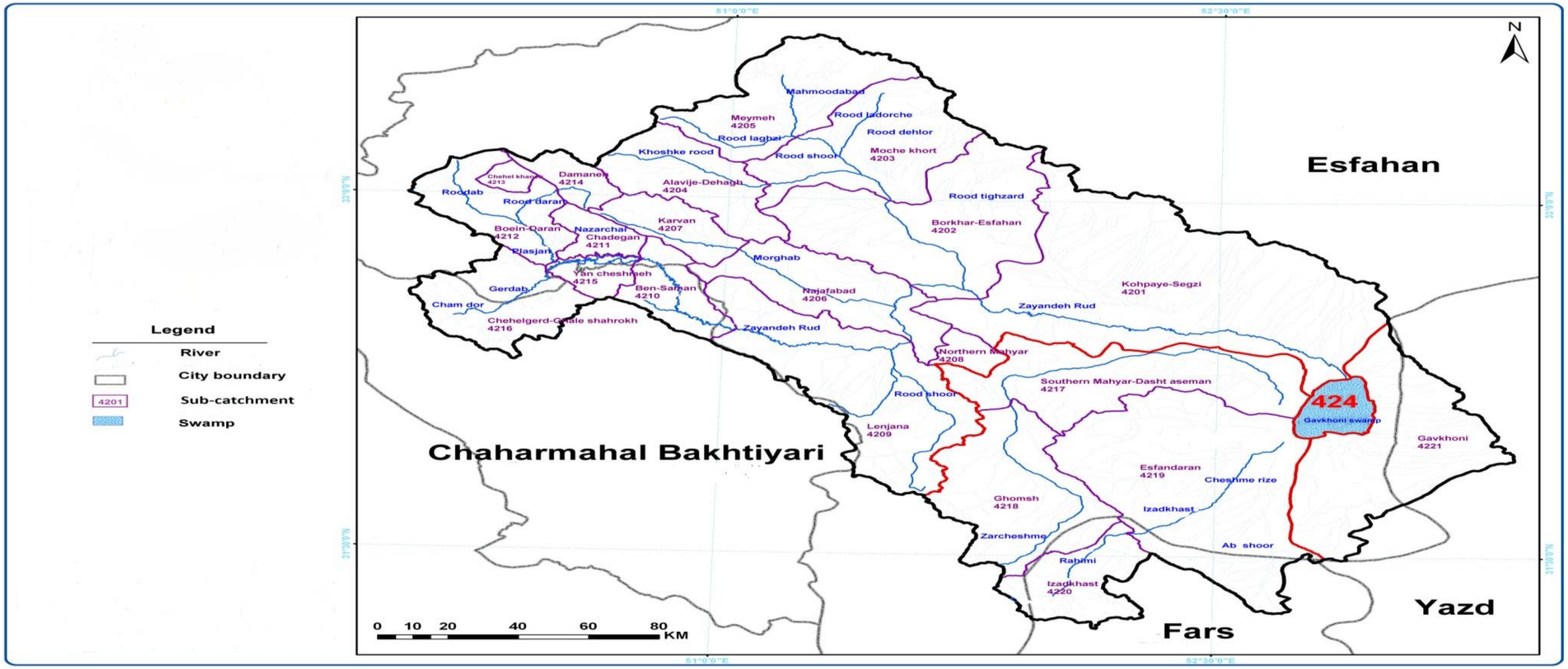


Figure 5.1: Map of the Zayandeh Rud sub-basins with main tributaries that were used for the WEAP model

WEAP is one-dimensional lumped or semi-distributed model. The WEAP model offers a choice of three methods to simulate hydrological basin processes such as evapotranspiration, runoff, infiltration and irrigation demands:

1) Irrigation demands only method

The easiest method of the three, which uses crop coefficients to calculate potential evapotranspiration in the basin. The portion of evapotranspiration which cannot be met by precipitation is thereafter estimated. This method cannot simulate runoff or infiltration processes.

2) Rainfall – runoff method

This method also calculated the evapotranspiration for irrigated and rainfed crops using crop coefficients. The portion of rainfall not applied for evapotranspiration is then converted to runoff to a river and groundwater.

3) Soil moisture method

This method is a one-dimensional, two subdivision soil moisture scheme, established by empirical functions defining evapotranspiration, surface and sub-surface runoff and deep percolation within the basin. Two options for routing the deep percolation are available: namely, as base flow to surface water body, or groundwater storage directly, if a groundwater link is made. However, this method for successful analysis needs a comprehensive soil and climate parameterisation.

In this research the rainfall-runoff method was selected because it captures the hydrological process accurately and because of the availability of data for its successful setup.

The different parameters needed by WEAP have been derived from several sources using various methods of analysis. Spreadsheet and GIS techniques have been applied because they offer extensive data analysis options with faster outputs. Therefore, some input data were in the Shapefile (.shp) format and some others in the (.xlsx) format.

The setting up of the rainfall-runoff method includes populating parameters for two main variables known as climate and land use. These two variables are then divided into sub-variables which are outlined in the data section (section 5.3).

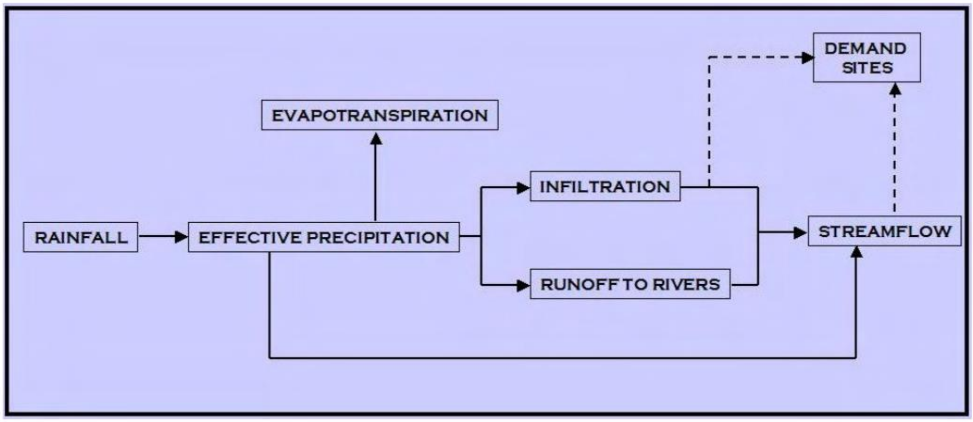


Figure 5.2: Schematic of WEAP rainfall-runoff component

Effective precipitation is the percentage of rainfall available for evapotranspiration. If not equal to 100%, the remainder is available for runoff.

Evapotranspiration is measured using the equation:

ET=Min (ETpotential,Precip)

With:

ETpotential=ETref×Kc×Area

Precip: effective precipitation

ETref: reference evapotranspiration

Kc: crop coefficient

Area: area over which evapotranspiration is measured

The rainfall amount that is not evapotranspired is available for infiltration and runoff. Exclusive of rainfall intensity, the amount of rainfall going to runoff (or groundwater) is specified as a percentage of the amount of water still available after evapotranspiration has appeared.

Runoff coincides with the fast response of the catchment and is thus turned into river stream flow directly; infiltrated water (slow response) goes to aquifer and maybe is released to rivers after a defined amount of time.

The variables needed to identify the aquifer are:

Storage capacity (mm3): the maximum theoretically available capacity of the aquifer.

Initial storage (mm3): water stored at the start of the first month of the simulation.

Hydraulic conductivity (m/day): the ability of the aquifer to transmit water over its pores.

Specific yield: porosity of aquifer, shown as a fractional volume.

Natural recharge (%): inflows to the groundwater source by rainfall.

Storage capacity below river level (mm3): groundwater storage volume where the top of the groundwater is level with the river.

The fixed components of the water allocation model of WEAP include(Moneo Laín, 2008, Yates et al., 2005):

- Rivers
- Diversions
- Reservoir
- Groundwater
- Demand sites
- Infiltration/runoff
- Transmission links
- Wastewater treatment plants
- Return flows
- Streamflow gauges

- Flow requirements

Following section 5.3, the details of the components that are used in this study are provided. Figure 5.3 represents the conceptual schematic of the structure of the river basin, where supply and demand components have been included.

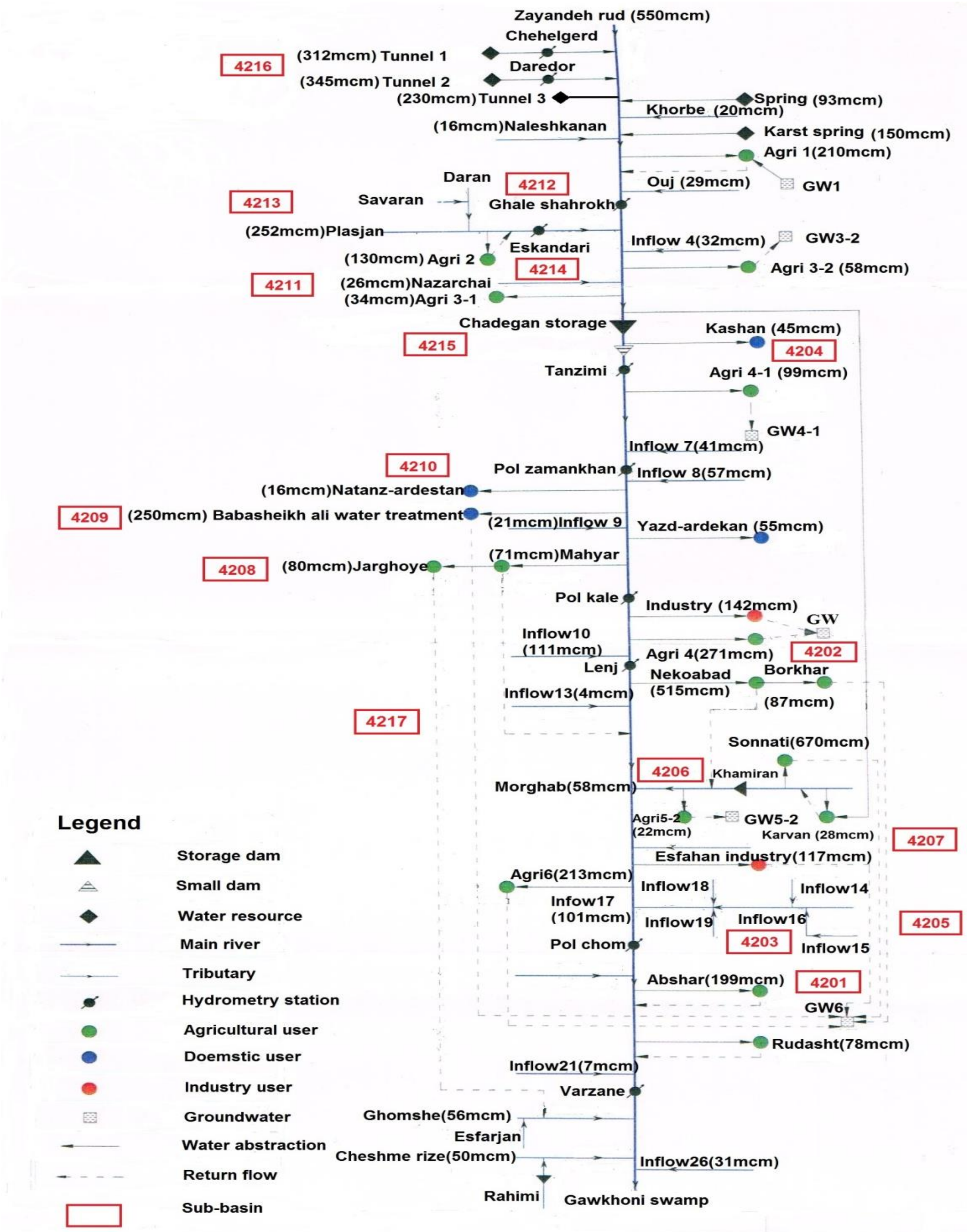


Figure 5.3: Conceptual model for the Zayandeh Rud river basin system includes water supply and water demand

5.2.3 Sensitivity and calibration

Table 5.2 is a list of the parameters applied in the model. Despite the model being a simple view of the real hydrological process, it still relies on a large set of parameters. So it was decided to reduce the number of parameters that were applied in the calibration routine, and measured values derived from the literature were applied to most of the parameters.

Table 5.2: Parameters used for WEAP simulation

	Parameter	**Value**
Catchment	Area (km^2)	Data
	Precipitation (mm)	Data
	Effective precipitation	Unfixed parameter (used for sensitivity analysis)
	Reference evapotranspiration (mm)	Data
	Crop coefficients	Data(used for sensitivity analysis)
Runoff and Infiltration	Runoff/infiltration ratio	Unfixed parameter (used for sensitivity analysis)
Groundwater	Storage capacity (MCM)	Unlimited
	Initial storage (MCM)	0
	Hydraulic conductivity (m/day)	Data (used for sensitivity analysis)
	Storage at river level (MCM)	0

Two sensitivity parameters were kept variable for the calibration approach; one for each step of the hydrological process modelled in WEAP (effective precipitation, runoff/infiltration). They were selected since they are the parameters that are most likely to be dependent on the catchment characteristics and also there is no common value which could be implied from the data. The parameters that are used for the aquifer characteristics are likely to be different in between sub-catchments. However, most of them are fixed; because there is no valid and sufficient data. It was decided to keep them fixed to develop the robustness of the simulation. The number of parameters to be changed was kept to a minimum; as the fixed parameters were based on credible sources

(Iranian Ministry of Energy and Isfahan Regional Water Authority). It was assumed that the climate data (as fixed parameters) are good quality, and should not be modified. The calibration was from 1997 to 2003, the period for which naturalised and precipitation time series are available.

A manual optimisation had to be achieved by a trial and error routine (Gorgens, 2015). Despite the method taking a lot of time; the advantage is it gives a good idea about model structure and model sensitivity to the different parameters.

Following the procedure of calibration, the efficiency criteria determine the best set of the unfixed parameters.

To calibrate the rainfall-runoff component of the model, the simulated flows against naturalised flow series (observed flow) in three stations for six years were used. There are a large number of objective functions and efficiency criterion that can be applied to determine the goodness-of-fit of the simulation. A brief summary of efficiency criteria often used for rainfall-runoff calibration and validation is shown below.

5.2.3.1 Coefficient of determination r^2

The coefficient of determination r^2 is determined as the square value of the coefficient of correlation according to Bravais Pearson (Krause et al., 2005). It is calculated as:

$$r^2 = \left(\frac{\sum_{i=1}^{n}(Oi - \overline{O})\,(Pi - \overline{P})}{\sqrt{\sum_{i=1}^{n}(Oi - \overline{O})^2}\,\sqrt{\sum_{i=1}^{n}(Pi - \overline{P})^2}}\right)^2$$

With O observed and P predicted values.

In addition, r^2 can be indicated as the squared ratio between the covariance and the multiplied standard deviations of the observed and predicted values. Therefore, it measured the combined dispersion against the single dispersion of the observed and predicted series. The range of r^2 is between 0 and 1, which explains how much of the observed dispersion is described by the prediction. A value of zero means no correspondence at all; whereas a value of 1 implies that the dispersal of the prediction is equal to that of the observation(Krause et al., 2005).

5.2.3.2 Nash-Sutcliffe efficiency E

Another efficiency criterion is to use Nash-Sutcliffe efficiency (1970).

$$EFF = 1 - \frac{\sum_{i=1}^{n}(Oi - Pi)^2}{\sum_{i=1}^{n}(Oi - \overline{O})^2}$$

Where $\bar{O}$ is the observed mean monthly flow over the whole period.

An efficiency criterion of 1 means that observed and simulated values are a perfect fit; while a negative criterion means that the simulation gives worse results than replacing simulated values with the observed mean monthly flow.

5.2.4 Current accounts scenario and baseline scenario

Making the hydrological element containing the head flows of the main river and all its tributaries, is the initial stage to characterise the model. The hydrological variables used in this study are given in the next section. The head-flow data was one of the variables used to assess water availability for the period of 1971-2005. Intra-year variability was studied to help understand the water demand and supply baseline situations during various seasons. Absence of regulation and rules to control water demand and supply as per season and precipitation events, during water shortage and surplus seasons the water demand remains unchanged and unaligned with water supply . To satisfy the WEAP model requirements, priorities were assigned to the water demands as per sectors: domestic water demand was assigned top priority, followed by industrial water demand and least priority given to demand of water in the agricultural sector. Average values of the variables has been used in the model to create the current accounts scenario.

5.2.5 Drought scenarios

Drought scenarios were constructed by selecting dry hydrologic years from the 1971- 2005. The dry years (consecutive dry years) obtained in Chapter 4. Drought indices estimated in Chapter 4 have been used to develop a drought scenario to calculate drought impacts on water allocation. So historical records of all data (see Table 5.1) for driest years was input to the model and can help to quantify the severity of the impact of drought on water resources and water demand satisfaction.

5.3 Data

5.3.1 Rainfall data

The primary input of the system is the data collection for rainfall between 1971 and 2005 in sub-catchments. Using data from the Esfahan meteorological stations having record lengths longer than 15 years, the study derived a rainfall time series of 17 stations to estimate precipitation in each sub-catchment and for the whole Zayandeh Rud basin.

5.3.2 Reference potential evaporation

Vegetation plays a significant role in the plant and soil water evaporation processes. In the Zayandeh Rud basin where agriculture is the main use of the land, evaporation is by far the largest water consumer of the catchment. Reference potential evaporation ETref has different definitions. In the current study, the monthly ETref is calculated by the Penman-Monteith equation. Reference evaporation for each sub-catchment (Figure 5.4) was computed from data from the meteorological station and reports of Moshaver Yekom Water Management Institution.

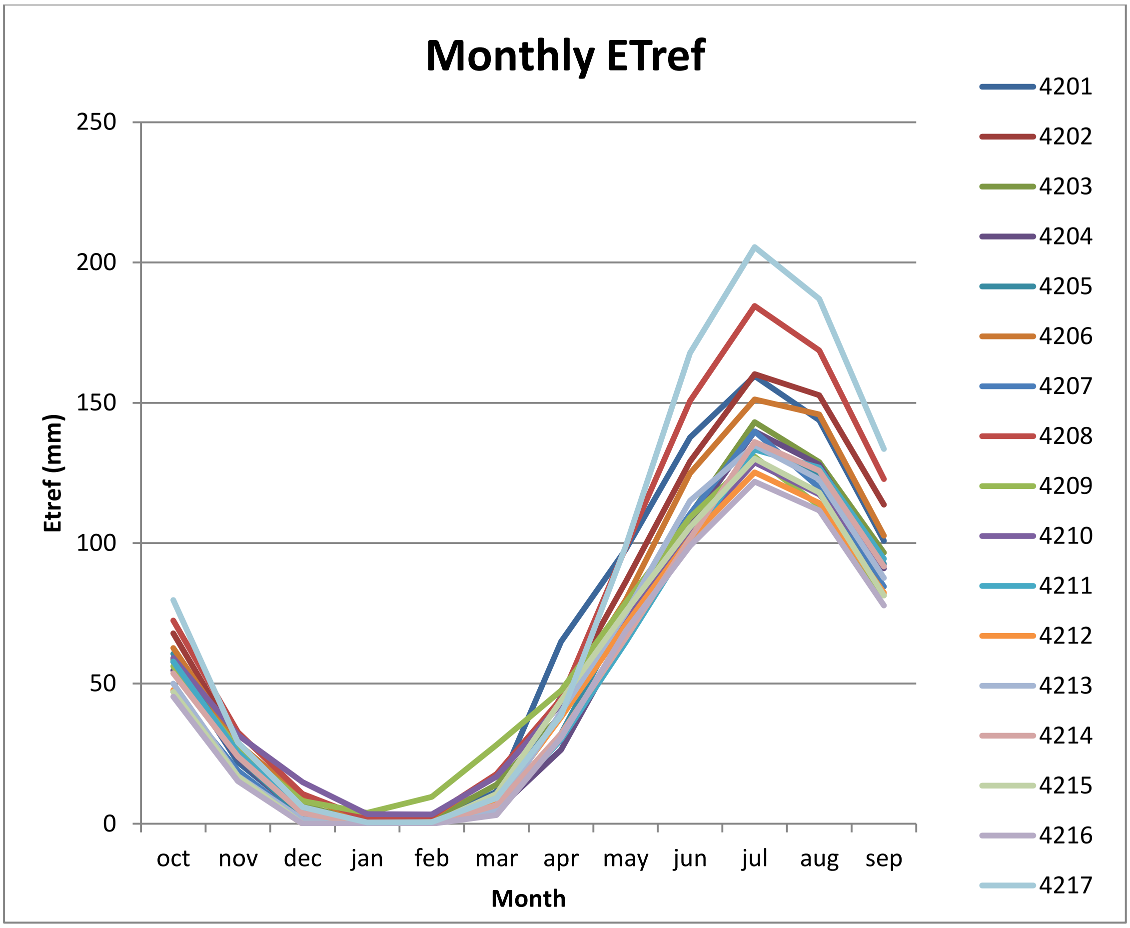


Figure 5.4: Monthly ETref in each sub-catchment.

5.3.3 Crop coefficients

Crop coefficient Kc is needed to estimate potential evaporation from a given land use type. It can be expressed as:

Kc=ETmax/ETref

It is the ratio of the maximum evaporation from the plant at given stage of growth (ETmax) to the potential reference evaporation (ETref). Sub-catchments could be merged into three groups of land type: irrigated area (69.38%), pastures (18.04%) and uncultivated area (12.57%). However, the greatest land uses have an irrigated area. In the WEAP model, monthly values of crop coefficients were extracted from the database of the Ministry of Agriculture in Iran, which comprises the crop coefficient for irrigated areas (main crops are rice, wheat, barley and potato) (Figure 5.5).

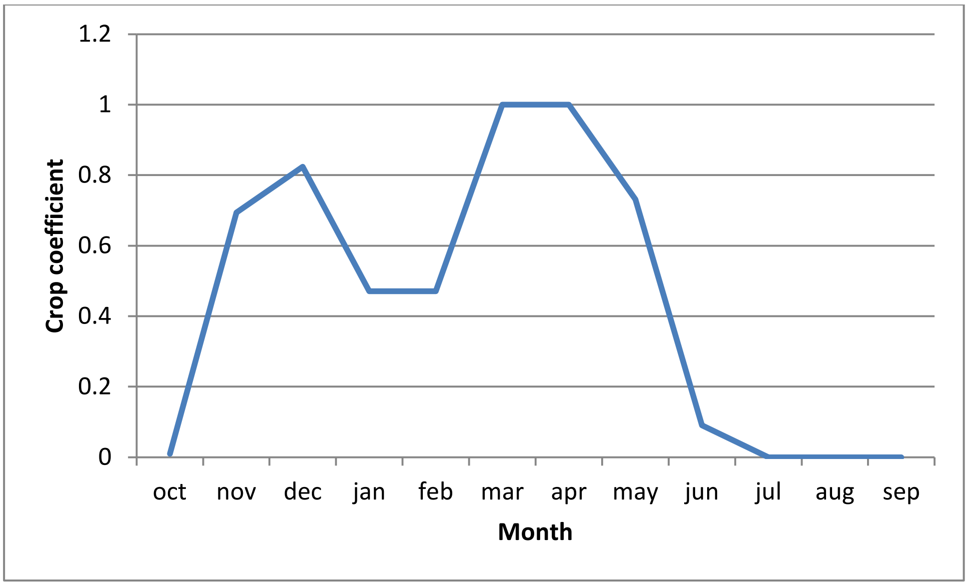


Figure 5.5: Monthly crop coefficients for all crops for the WEAP simulation

5.3.4 Inter-basin transfers

In the Zayandeh Rud basin, water is transferred both in and out the basin. The water from another neighbouring catchment is transferred into the basin by a net import of approximately 887 MCM water (trans-basin diversions by three tunnels). More details are in section 5.3.9.

5.3.5 Reservoirs

There is one major dam (which is known as Chadegan or Zayandeh Rud dam) and two minor dams with a cumulative capacity of 1488.65 MCM in the basin. The modelling of the reservoir in WEAP and more details are in appendix IV. For all the dams, storage-volume curves are needed for the structure of the model estimated from ERWA. For the dams, operation rules do not identify from ERWA and consequently only very simple operating rules (similar to other studies such as Arranz et al. (2007) and (Mugatsia, 2010)) and were imposed in the management of the dams in WEAP as shown in Table 5.3.

Table 5.3: Reservoirs explicitly included in WEAP simulation

Dam	River	Located in WEAP sub-catchment	Current Height (m)	Current storage (MCM)	Top of inactive (MCM)	Top of conservation (MCM)	Net evaporation (mm)
Zayandeh Rud	Zayandeh Rud	4215	100	1470	20	1450	1612
Khamiran	Zayandeh Rud	4206	6	6.65	0.15	6.5	1763
Izadkhast	Zayandeh Rud	4207	12	12	1.5	10.5	2082

5.3.6 Groundwater

Knowledge about aquifers' characteristics is relatively poor in the Zayandeh Rud basin. It was not possible to infer parameter values needed for the WEAP model. Therefore, some assumptions had to be made to design aquifers in WEAP.

- For each sub-catchment storage capacity of the aquifer was supposed to be unlimited. It was assumed partly because, in WEAP, infiltration of water to a full aquifer is lost from the system. Therefore, no overflow of groundwater was possible. However, it was verified that groundwater storage was not reaching unrealistic values.
- Initial storage was assumed to be null as no data were available about the storage in 1971. It is expected to affect most the first five years of simulation and to have a weak impact on the overall results. In the results section, only the biggest aquifer in the Zayandeh Rud basin was analysed.
- The aquifers of the model were simulated on the same pattern. Specific yield of each aquifer was fixed at 0.2 (average value estimated from((ERWA), 2005).
- Storage at the river level was supposed to be equal to 0. It means that in the simulation, no water could be transferred from the river to the aquifer.
- Hydraulic conductivity was fixed in the model.

5.3.7 Flow in the catchment

Measured flow

Common features of the flow data in the Zayandeh Rud basin of 17 different flow gauging stations managed by the Ministry of Energy and Esfahan Regional Water Authority (ERWA):

-Flow decreases from upstream (mostly in western part) to downstream (mostly in the east part)

-Flow records show high seasonal variability

Naturalised flow

The details of explanation of naturalized flow are presented earlier in Section 3.4.2.1 in Chapter 3. Using data available from three different gauging stations in the Zayandeh Rud basin for 1971-2005 simulated naturalized flow; Water losses due to evaporation, land cover and water consumptions were modelled, and the simulated flow was calibrated against measured flow. Naturalised flow sequences were generated by running the model again with all land use components and water demands to understand the impact of human activities on flows in driest years during drought periods.

In addition, naturalized flow time-series were used for calibration of the model in sub-catchments upstream, midstream and downstream. Monthly time-series of cumulative flow was used in the WEAP model. Area and mean annual naturalised flow for each sub-catchment are shown in Figure 5.6.

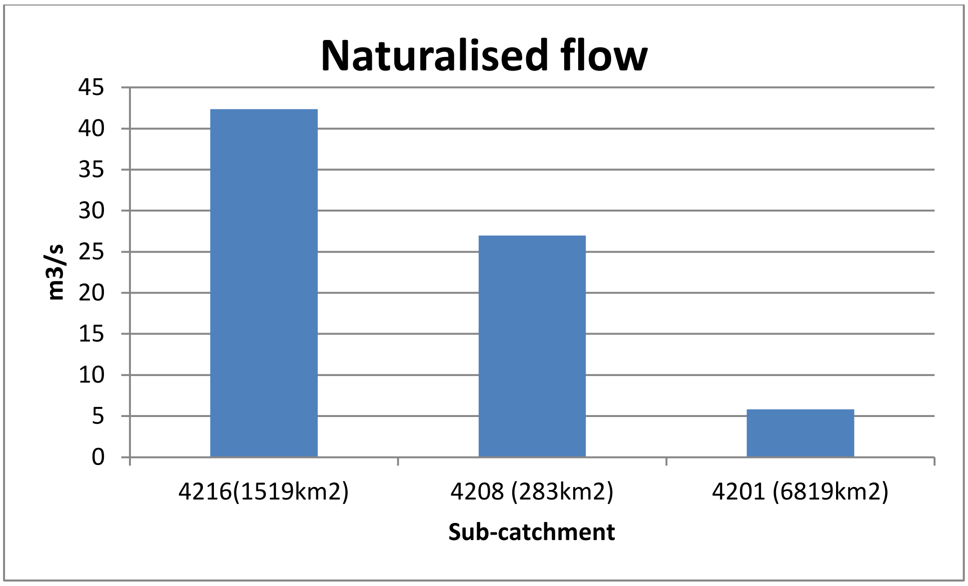


Figure 5.6: Area and mean annual naturalised flows and in upstream (sub-catchment 4216), in mild-stream (sub-catchment 4208) and downstream (sub-catchment 4201) of the Zayandehrud basin.

5.3.8 Other water resources

Most of the surface runoff is generated from the higher rainfall in the mountainous parts of the basin. The Chadegan Reservoir upstream can use to estimate the natural hydrology of the basin. The mean annual surface runoff in the basin is about 900 MCM. It is increased by a net import of water (trans-basin diversions by three tunnels) into the basin of 850 MCM to 1487MCM.

There are a few springs and other natural sources of water that are still under development, with a cumulative annual yield of about 150 MCM.

In the Zayandeh Rud basin without the tunnels, current levels of economic development are not able to be sustained.

5.3.9 Water user and trend of the demand

Irrigation is the biggest consumer of water within the Zayandeh Rud basin (see Figure 5.8). Between 1965 and 2000 the irrigated area was approximately raised from 40000ha to

289888ha ((ERWA), 2005). There is no quantitative data available for the years before 1988. Within WEAP, the annual demand was shown as a volume per hectare irrigated, however, return flows were presented as a percentage of the demand, and return flows certainly depend on the rainfall and the crop irrigated. The percentage of return flow was assumed to be the same in all years. As shown in Figure 5.7, the return flow values are low (between 8 to 13%) for all sub-basins.

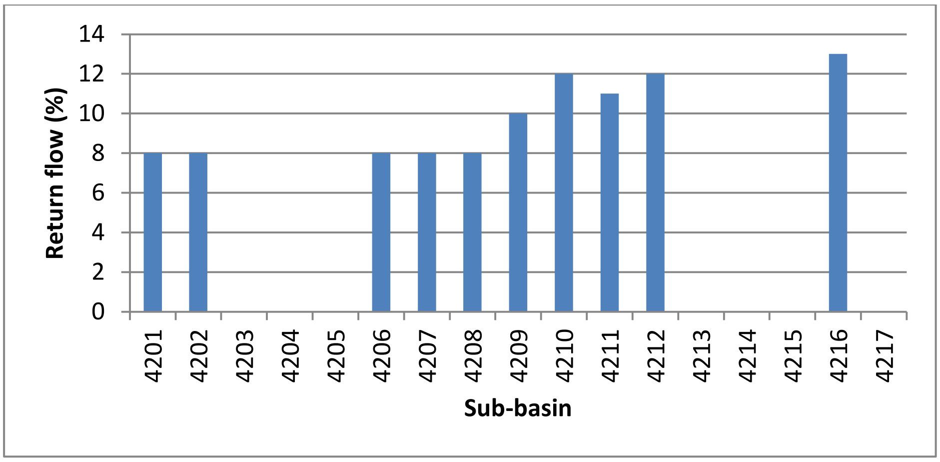


Figure 5.7: Return flows for the sub-basins

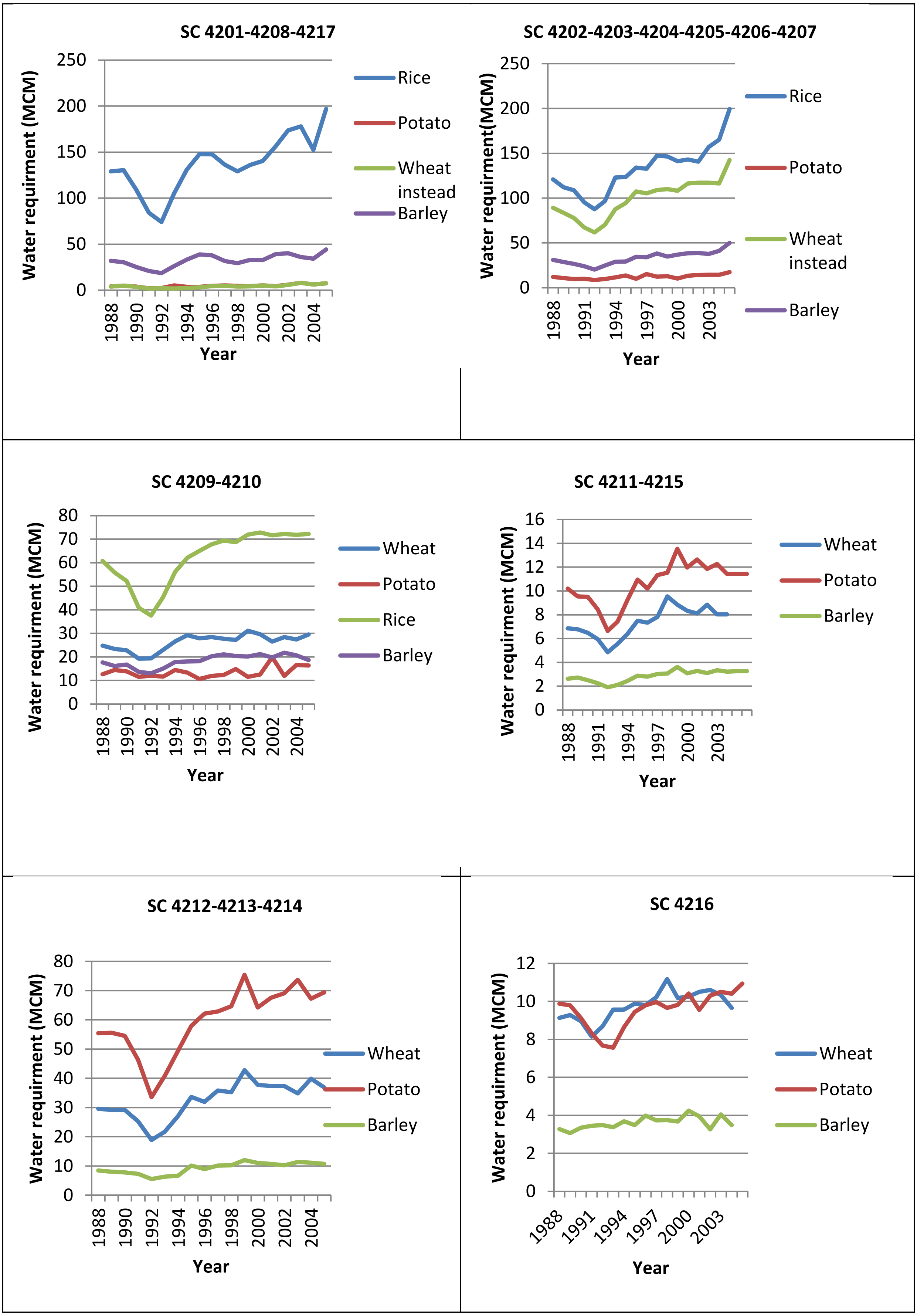


Figure 5.8: Water requirement for each crop in different sub-catchments

The most water demands as shown in Figure 5.4 in appendix are agriculture, industry and domestic. However, the best priority for water use is domestic the second is industry, and agricultural water is the third.

All the current water demand patterns are listed below:

Urban demand (domestic and small industrial demands)

At present, with a population of 3 million, water availability per capita is 250 l/day (or 210 MCM per year). The high per capita figure results in part from high conveyance losses in transmission, high demand during the summer when temperatures are raised, and demands from small-scale industries associated with the urban water supply. The urban supplies originate from several sources: more than two-thirds come from the Baba Shakh Ali treatment plant, which gets water directly from the Zayandeh Rud deviation upstream of Esfahan, the rest coming from the Felman Wellfield which is restored by Zayandeh Rud water.

Of total water diversions (approximately) 50% of urban demand is returned to the river that can be applied to downstream irrigation systems. However, it is lower than often used in return flow measurements because a huge volume of wastewater is used to grow trees around Esfahan city and major industrial areas.

Industrial demand

There are specific significant industrial water consumers in the basin who have their water demands: cement works, steelworks, iron smelter, oil refinery, polyacrylic plant and electricity generation; their demands total 200MCM.

Agricultural demand

There is approximately 600,000 ha of irrigated land in the basin. The total annual demand is 2000MCM. This makes agriculture the most significant single demand for water in the basin.

Similar to urban areas, there is high return flow from irrigated lands to the river, and we estimate this to be in the order of 30-40% of total abstractions. Upstream return flows are probably much higher than the tail end systems. Therefore, agriculture is a net user of about 1400 MCM.

Environmental demand

Currently, there is no specific allocation of water for in-stream needs or protection of Gavkhouni Swamp; however, the Environment Organization of Esfahan determines a minimum flow (70 MCM per year) into Gavkhouni Swamp.

5.4 Results

5.4.1 Framework for the demonstration of outcomes

Simulations outcomes are indicated through figures made by the data provided via WEAP for resource and requirement quantities. However, at first, sensitivity and calibration analysis are shown. Then, for the "current accounts" scenario, beginning via the baseline scenario through mean rainfall and inflow quantities; for the drought scenario with rainfall and streamflow quantities in dry years, without drought control analysis; and lastly results from values of different scenarios for impacts of drought on water supplies. Unmet demands are compared for better understanding and analysis. Furthermore, the human impact on water supply under different scenarios has been determined. The data available for the area under cultivation was not for each sub-catchment. However, it was available for a group of sub-catchments. Therefore, in the results from section 5.4.3 onwards, some results are shown for a panel of the sub-catchments. This structure will be repeated for the future climate alteration scenarios with and without the application of management measures for the Zayandeh Rud river basin in the following chapters.

5.4.2 Sensitivity and model calibration analysis

5.4.2.1 Sensitivity parameters

The values of the different sets of parameters found in the model are reviewed by:

- Effective precipitation: In WEAP model, this only refers to the precipitation uptake by plants and not the amount of precipitation that generates streamflow. It ranges from 91 to 99.5%. The highest values are found in mountainous regions (4216) and the lowest values are reached in flat regions (4201). Usually effective precipitation (i.e. precipitation available for evapotranspiration) relates to the intensity and duration of a rainfall event. It is assumed that in sub-catchments that are located at high elevation, the effective precipitation is lower, which corresponds to the values found in the model.
- Runoff/infiltration: the ratio ranges from 70/30 upstream to 30/70 downstream. Groundwater recharge in the Zayandeh Rud basin is about 5% of mean annual rainfall. It indicates much lower values for runoff fraction.
- Hydraulic conductivity: the values of hydraulic conductivity are about 0.8 metres/day, and they are fixed parameter s for all sub-catchments. However, for better understanding, the sensitivity of the model is changed to measure how variations in hydraulic conductivity affect the flow.
- Crop coefficient: the annual mean values of crop coefficients are about 0.9, and they are a fixed parameter. However to estimate the sensitivity of the model it is changed -10% and +10%.

5.4.2.2 Sensitivity analysis

A sensitivity analysis was executed to assess the sensitivity of the model to several parameters (especially unfixed input parameters) applied for calibration. The sensitivity of the model to the parameters was determined by estimating effects of changes in parameters of the simulated flow and the Nash-Sutcliffe efficiency criterion in sub-catchment 4201, which is located downstream. Table 5.4 shows the results of the sensitivity analysis. The mean annual flow was applied as a standard for model behaviour. The change in efficiency parameters for different changes in effective precipitation, runoff/infiltration ratio, hydraulic conductivity and crop coefficient is given in Table 5.4. Mean monthly flows in Figures 5.9 to 5.12 were also shown and compared.

Table 5.4: Variation of the mean annual simulated flow due to changes in the parameter values in the 4201 sub-catchment

Parameter	Value	Mean annual flow (MCM)	E
Effective precipitation	91	130.7	0.86
	89	163.1	0.83
	93	98.8	0.83
Runoff/infiltration ratio	40/60	130.4	0.86
	35/65	130.0	0.70
	45/55	130.5	0.90
Hydraulic conductivity(m/day)	1.4	130.9	0.59
	0.6	130.7	0.70
	1	130.6	0.88
Crop production	+20%	80.7	0.77
	-20%	193.7	0.49

The sensitivity analysis, as shown in Table 5.4, indicates that just effective precipitation and crop coefficients have a significant impact on the mean annual flow. Therefore, it seems effective rainfall has great impact on the model's efficiency. Compared to the other parameters, effective precipitation has a relatively small impact on the quality of the simulation (lowest variation of the Nash-Sutcliffe efficiency criterion). It means with change ±2 for the effective rainfall value, the E value change is 0.03. However, hydraulic conductivity and crop coefficients' variations seem to have a significant impact on the model efficiency. It means with change ±0.4 in the value of hydraulic conductivity, the E value change is 0.18 and 0.29. In addition, with a change ±20% in the crop coefficient values, the E value change is 0.28. Figures 5.9 to 5.12 show how all parameters affect the mean monthly flow curve without significantly affecting the relative flow in each month.

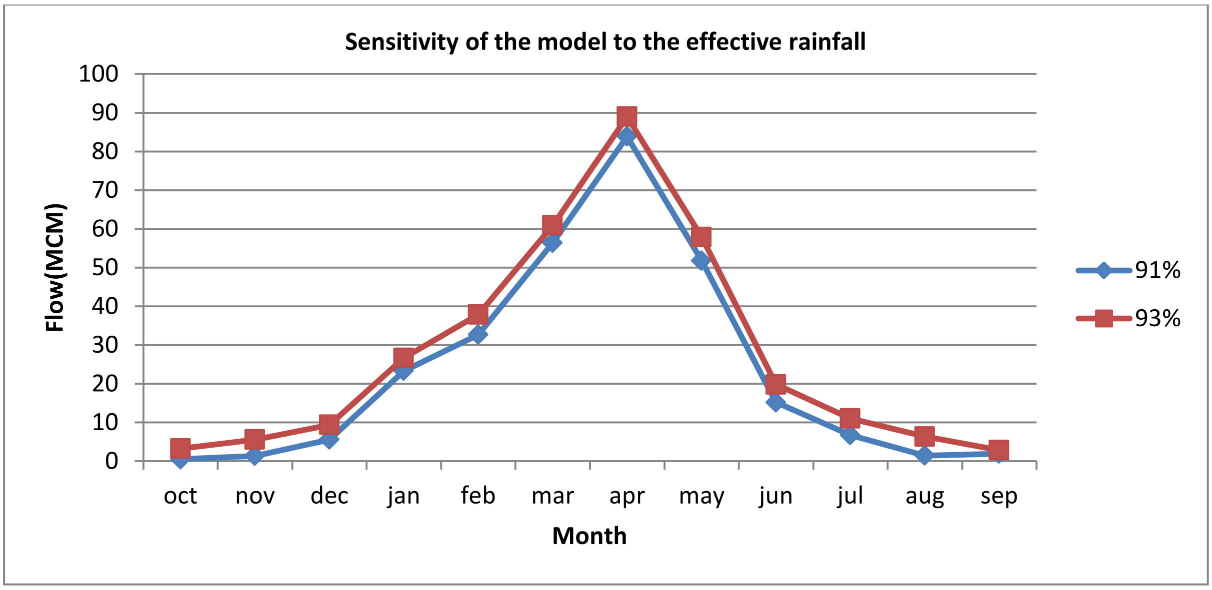


Figure 5.9: Change in simulated mean monthly flow due to effective precipitation variation

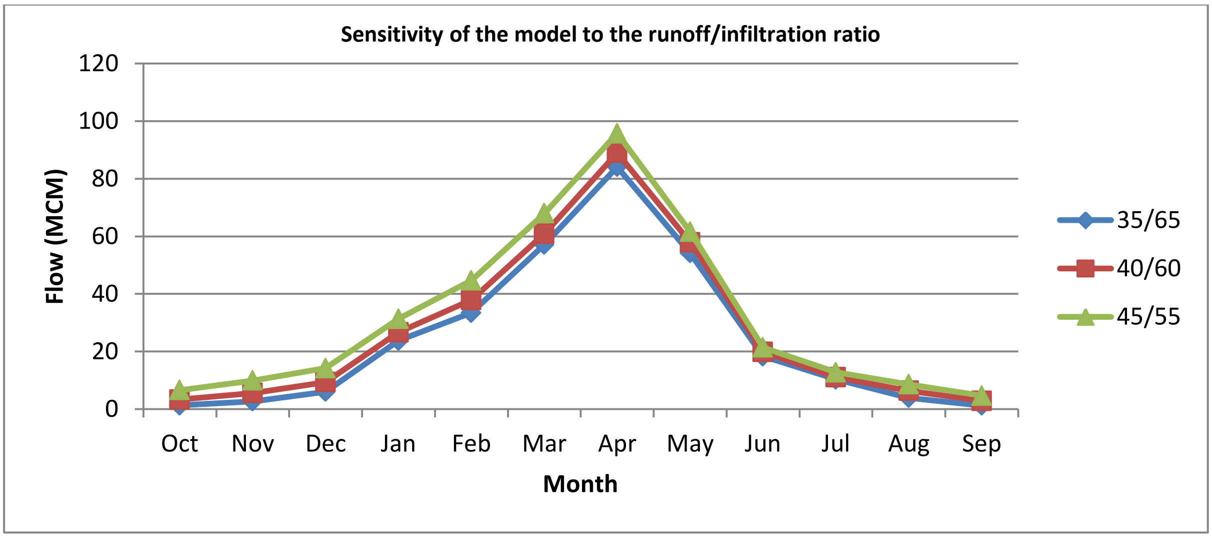


Figure 5.10: Change in simulated mean monthly flow due to runoff/infiltration variation

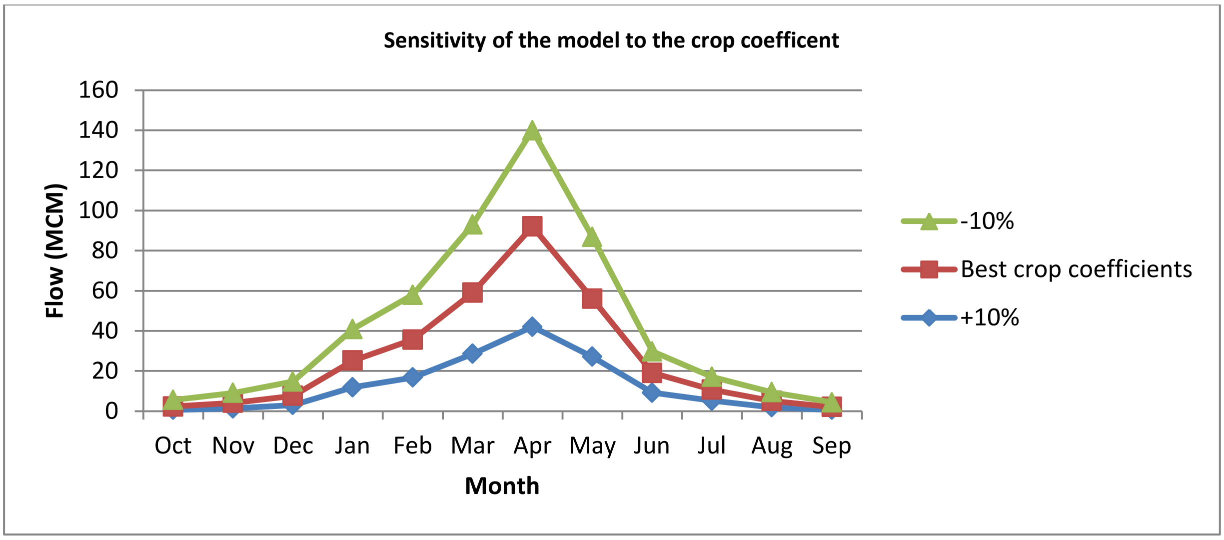


Figure 5.11: Change in simulated means monthly flows due to crop coefficient variation

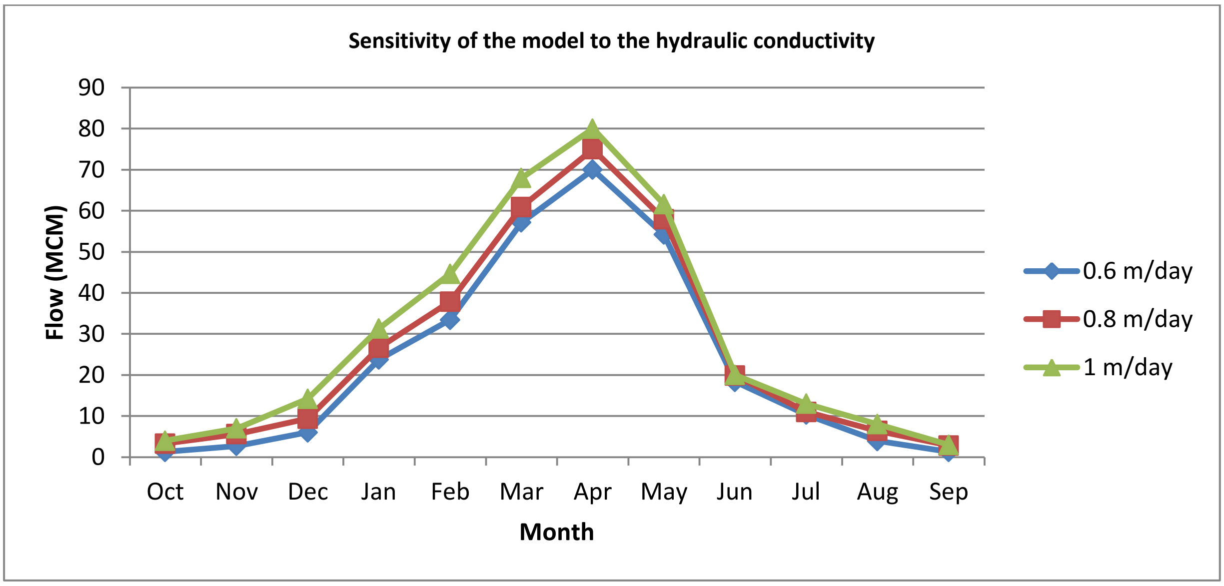


Figure 5.12: Change in simulated means monthly flows due to hydraulic conductivity variation

5.4.2.3 Calibration

5.4.2.3.1 Calibration steps

- ✓ There is no optimisation routine included in the WEAP model; a manual optimisation had to be achieved by a trial and error routine.

- ✓ One calibration procedure was used. It aimed to optimise the efficiency criterion objective (e.g. E and R2) by determining the best set of the unfixed parameters.
- ✓ Two parameters (effective precipitation and runoff/infiltration) were kept unfixed for the calibration; one for each step of the hydrological process modelled in WEAP (evaporation, runoff/infiltration). They were selected because they are the parameters that are most likely to be dependent on the catchment characteristics and for which no common values could be inferred from the data.
- ✓ From the initial set of parameters, one parameter was changed at a time until the routine could not optimise the assessment criterion any more.
- ✓ The ranges for the unfixed parameters were derived from the literature (hydrology reports for the basin for water balance from Iran's Ministry of Energy for 40 years). For example, the reports mentioned the mean annual effective precipitation is quite high in the basin. Therefore, it was assumed the initial value started from 100% for the effective precipitation and then changed to get the best value of efficiency criteria.

5.4.2.3.2 Initial parameters

Through the initial set of parameters (Table 5.5), one setting was changed at a time until the routine could not optimise the assessment criterion (e.g. $R^2$and E values) anymore.

Table 5.5: Unfixed parameter initial values and steps used for calibration WEAP

Parameter	Initial value	Step
Effective precipitation	100%	±0.5
Runoff/infiltration ratio	50/50	±5/5

5.4.2.3.3 Calibration approach

At first, the model was run with the set of parameters indicated in Tables 5.2 and 5.4. This simulation showed that runoff measured by the model was higher runoff than observed flow (naturalised flow). It meant that not enough water was lost from the system in WEAP. It seemed that either evaporation from the model was low or there were losses in the naturalised flow that WEAP was not able to take into account; particularly because WEAP only simulates evaporation from plants and not evaporation from the soil. Furthermore, there may be an error in the crop coefficients' estimation. As the aim of the calibration is to simulate naturalised flow data and water losses had to be added. A multiplying factor was applied to each set up of crop coefficients to distinguish the right quantity of water. A common factor was estimation of agricultural land use type (the most important land use in this study) by running the model and comparing mean simulated runoff with mean naturalised runoff. A value of 1.3 for the final multiplying factor was used for calibration of the WEAP. Simulated time series after adjustment in sub-catchment 4216 (upstream) and 4201 (downstream) are shown in Figures 5.13 and 5.14.

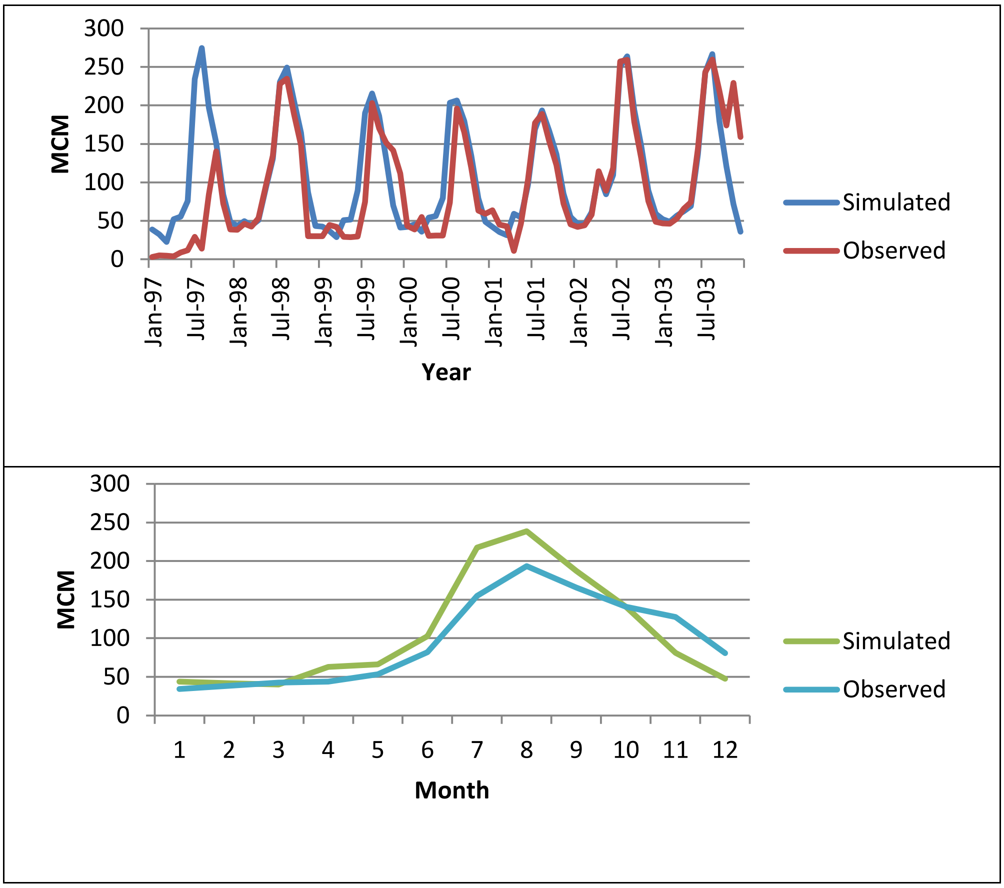


Figure 5.13: Compare simulated flow and observed flow in upstream using final parameter

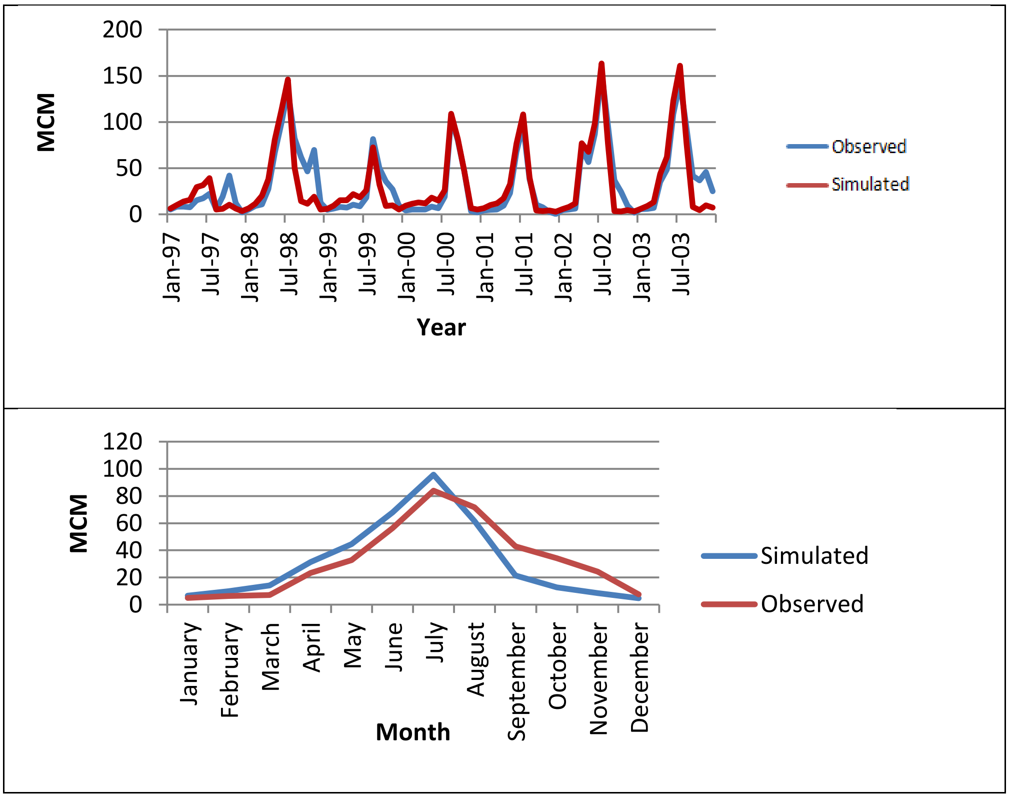


Figure 5.14: Compare simulated flow and observed flow in downstream using final parameter

The goodness of fit between simulated and naturalised values was assessed using two criteria: the coefficient of determination (R^2) and Nash-Sutcliffe efficiency (E) criterion. The best set of parameters was selected as that which made the best model fit by using the two criteria. Table 5.6 indicates the set of parameters that optimised the simulation and observation values. The assessment criteria related to each set of parameters, and compared the simulated and naturalised mean annual flow. The overall criterion for the three sub-catchments is high which means that errors of the model are low.

Table 5.6: Results of calibration for three sub-catchments

Sub-catchment	**Effective precipitation**	**Runoff/infiltration**	R^2	**E**	**Ratio of simulated and naturalised mean annual flow**
4216	98	70/30	0.93	0.87	1.03
4208	96.3	65/35	0.91	0.85	1.15
4201	91	40/60	0.93	0.86	1.10

5.4.3 Water allocation model under reference scenario

5.4.3.1 Supply and demand analysis

As a first step, the head flows of the main river and all tributaries was analysed throughout the reference period. Figure 5.15 indicates inflows in the upstream (such as 4216, 4212 and 4215 sub-basins of the Zayandeh Rud river are greater than down-stream (such as 4201 and 4208 sub-catchments). Also in dry years specified in Chapter 4, the head-flows decreased compared to normal years.

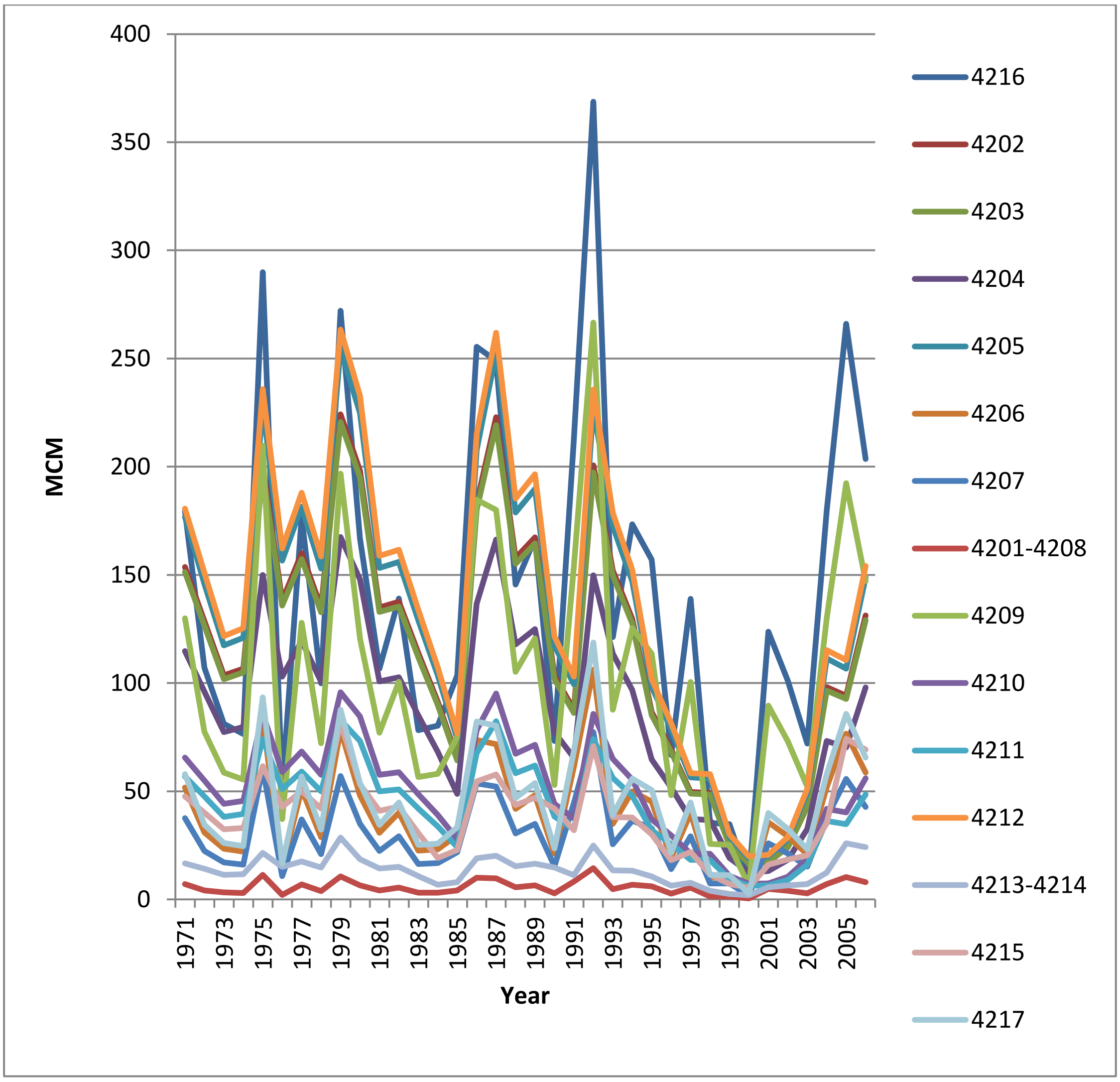


Figure 5.15: Head flows in the Zayandeh Rud river basin in the baseline reference scenario

The second step of water allocation is identifying the water consumers and water usage. Figures 5.16 and 5.17 show the mean annual (for the period of 1971-2005) water usage and mean monthly differences in water utilisation in the Zayandeh Rud basin. The figures represent changes of the water volume for different requirements. Overall, the irrigation areas in the down-stream of the basin use water volume much more than domestic and industrial sectors. These data are valuable for the designing water allocation plans since, even if urban demand does not vary during the year, irrigation requirments are higher in August and September (summer time) and this increase in demand needs to be considered for planning.

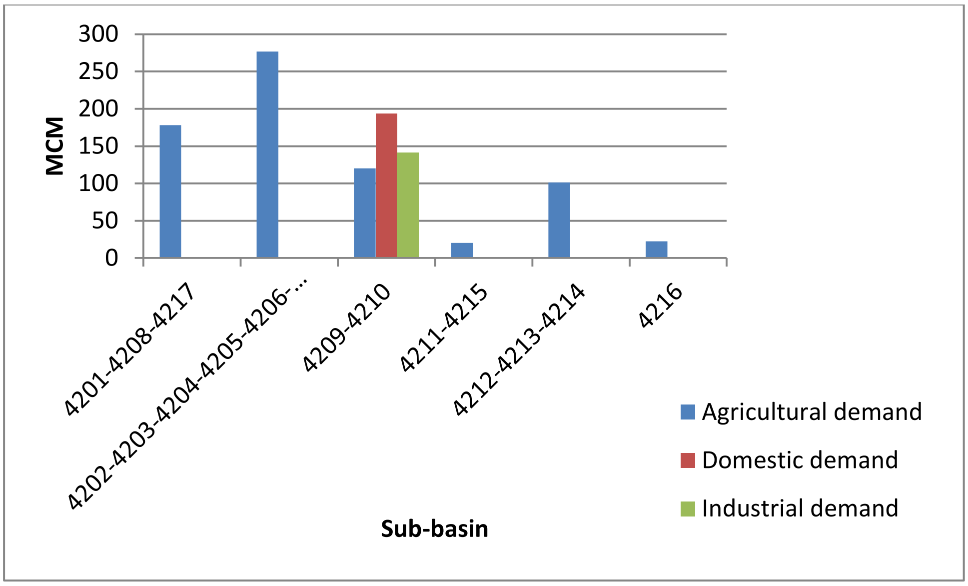


Figure 5.16: Annual water uses in the Zayandeh Rud basin

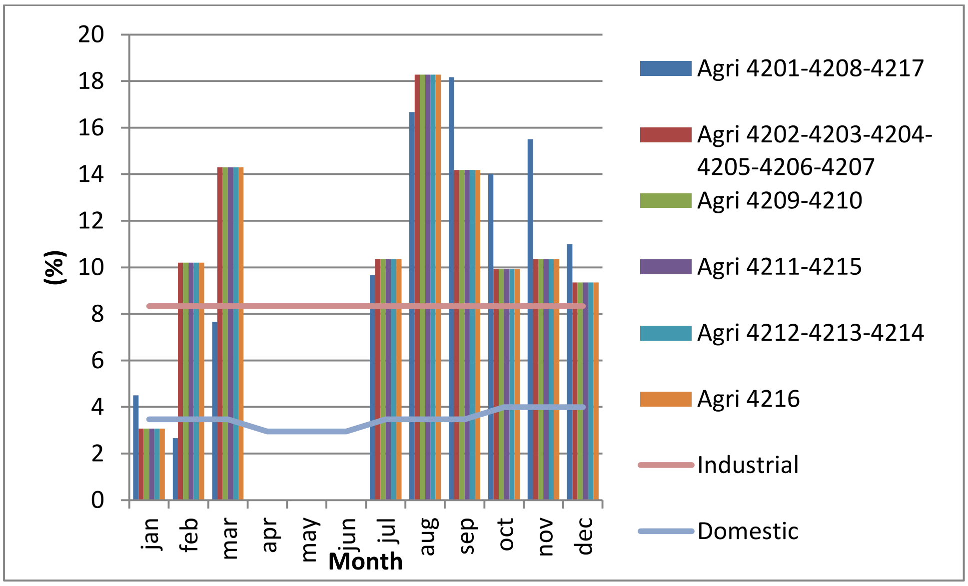


Figure 5.17: Monthly variations in water use in the Zayandeh Rud basin (% annual)

5.4.4 Water allocation model under drought scenario

5.4.4.1 Supply and demand analysis

Determining the "current account" as the reference can provide the condition for new values and new scenarios (drought scenario) in the model, to conrast the outcomes of water resources and water requirement gratification stage.

The drought scenario depends on different components. The reduction in inflow quantities and the growth of agricultural requirments are related to the crop dissemination area and rainfall decline. Therefore, a comparison between the reference scenario and drought scenario make a developing plan for management alternatives for future climate change and future drought.

The results indicate not only that supply changed for the drought years (Figure 5.18); but, all water users also had higher water requirements. This examination has been improved with a distinguishing crop dissemination area to find how agricultural requirments rise throughout drought scenario. The increases in agricultural water demands and other demands are indicated in Figure 5.19.

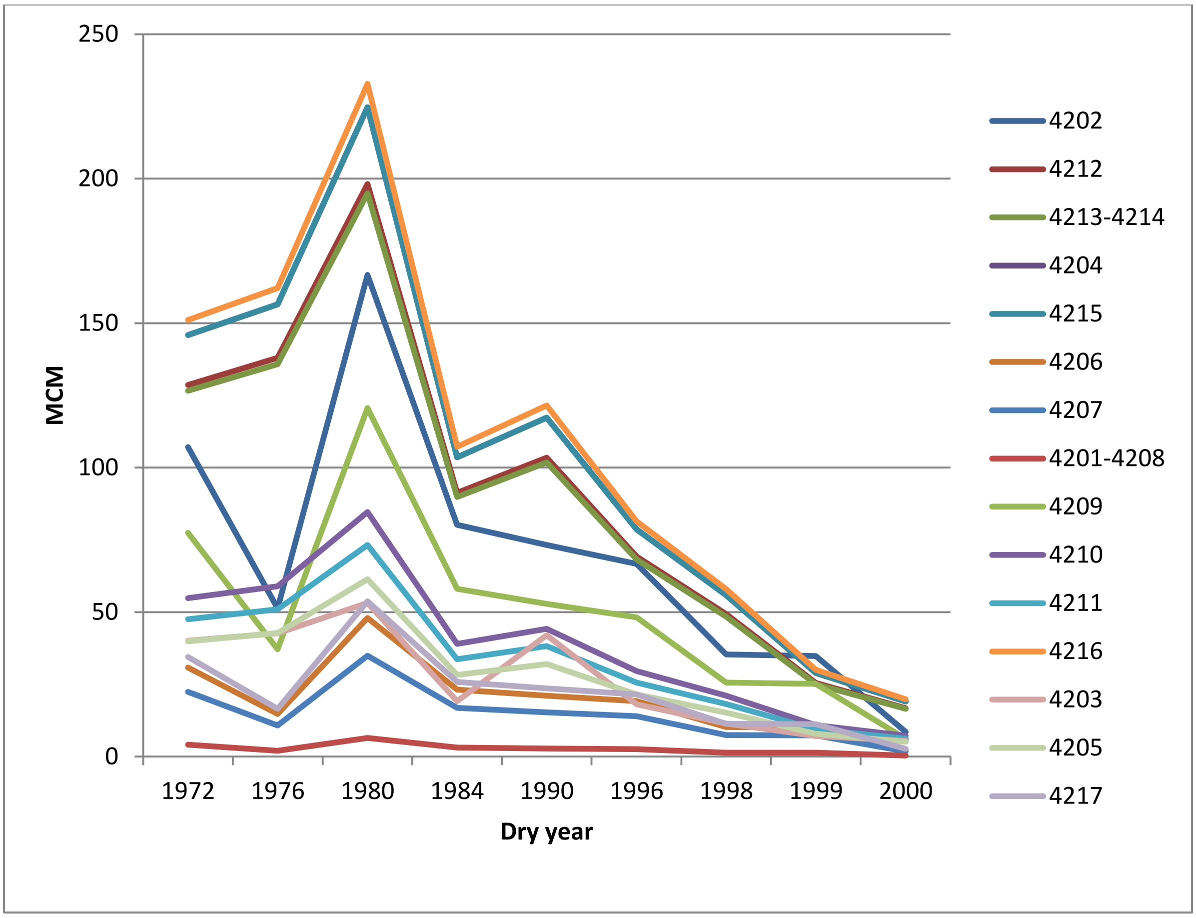


Figure 5.18: Head flows in the Zayandeh Rud river basin in the drought scenario

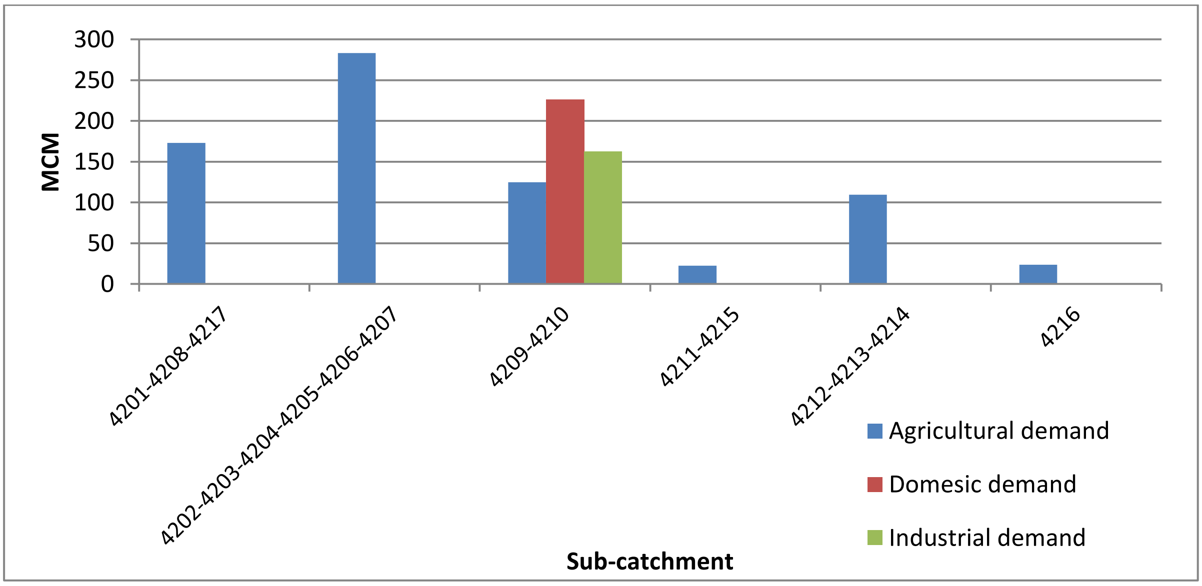


Figure 5.19: Annual water uses in the Zayandeh Rud basin in the drought scenario

5.4.5 Compare water allocation model under reference and drought

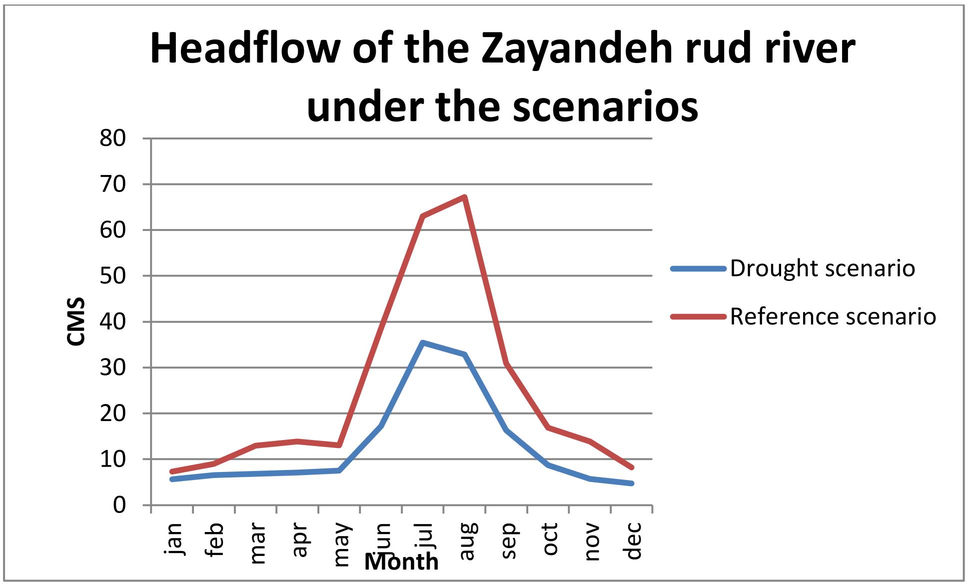


Figure 5.20: Head flow of the Zayandeh Rud Main River in reference and drought scenario

Figure 5.20 represents the values for head flow (average monthly inflow at head of the river) simulated in the reference and drought scenarios for the Zayandeh Rud river. It is interesting to notice the difference between the head flow during reference and drought scenarios is much higher in the summer months than in cold months. Also, inter-annual variability is much higher during the spring and summer flow season.

Figure 5.21 shows the values of groundwater storage during normal and drought conditions. In the normal years, the groundwater storage is higher than in dry years; as the abstraction of water for irrigation demands has increased. The groundwater decreases by 31.83MCM during the drought scenario.

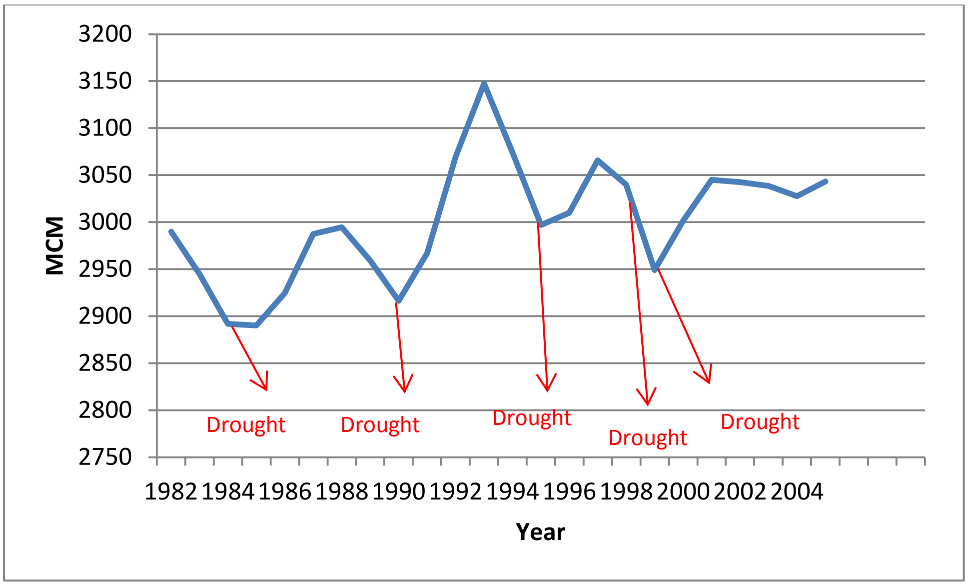


Figure 5.21 Groundwater storage of the Zayandeh ruds basin

The monthly unmet demand in the Zayandeh Rud basin is shown in Figure 5.5 in appendix. In WEAP, the irrigation demand was given the lowest priority; so in periods of drought and water scarcity, irrigation demand is curtailed to ensure that water requirements of the other sectors are met. For the reference scenario, the highest unmet demand occurred in summer and autumn months (see Figure 5.5 in appendix). The lowest unmet was during spring time because of the lowest demand. The high inter-annual variability of the unmet demand is associated with a change in irrigation demand arising from variation in rainfall.

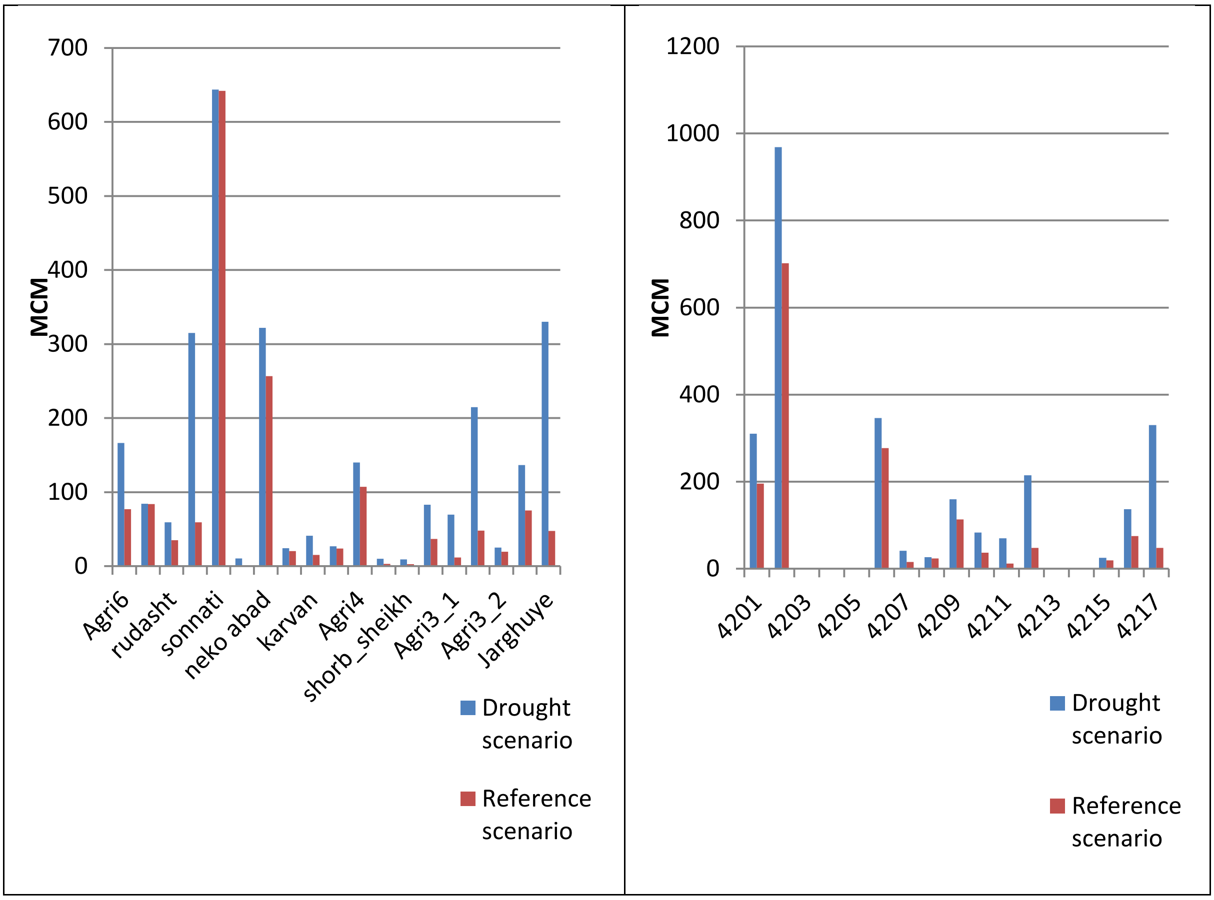


Figure 5.22: Compare sum of unmet demands in each water user sectors in left and sum of unmet demands in each sub-catchment in right in the Zayandeh Rud basin in the reference and drought scenarios

Figure 5.22 indicates that the most unmet demand during the reference and drought scenarios was measured for sub-catchment 4202; which has a large area under cultivation and the highest irrigation demand. The majority of the crop is rice which consumes much more water and irrigation efficiency in the sector of Sonnati. The second highest unmet demand belongs to the sub-catchments 4201 and 4217, which are located downstream and receive very low flow during a drought period. Due to the deficit in flow and the cropping season, which result in a higher demand for all sub-catchments between August and December, the unmet demand is much higher than in other months.

Figure 5.23 also mapped the percentage of total unmet demands in the sub-catchments.

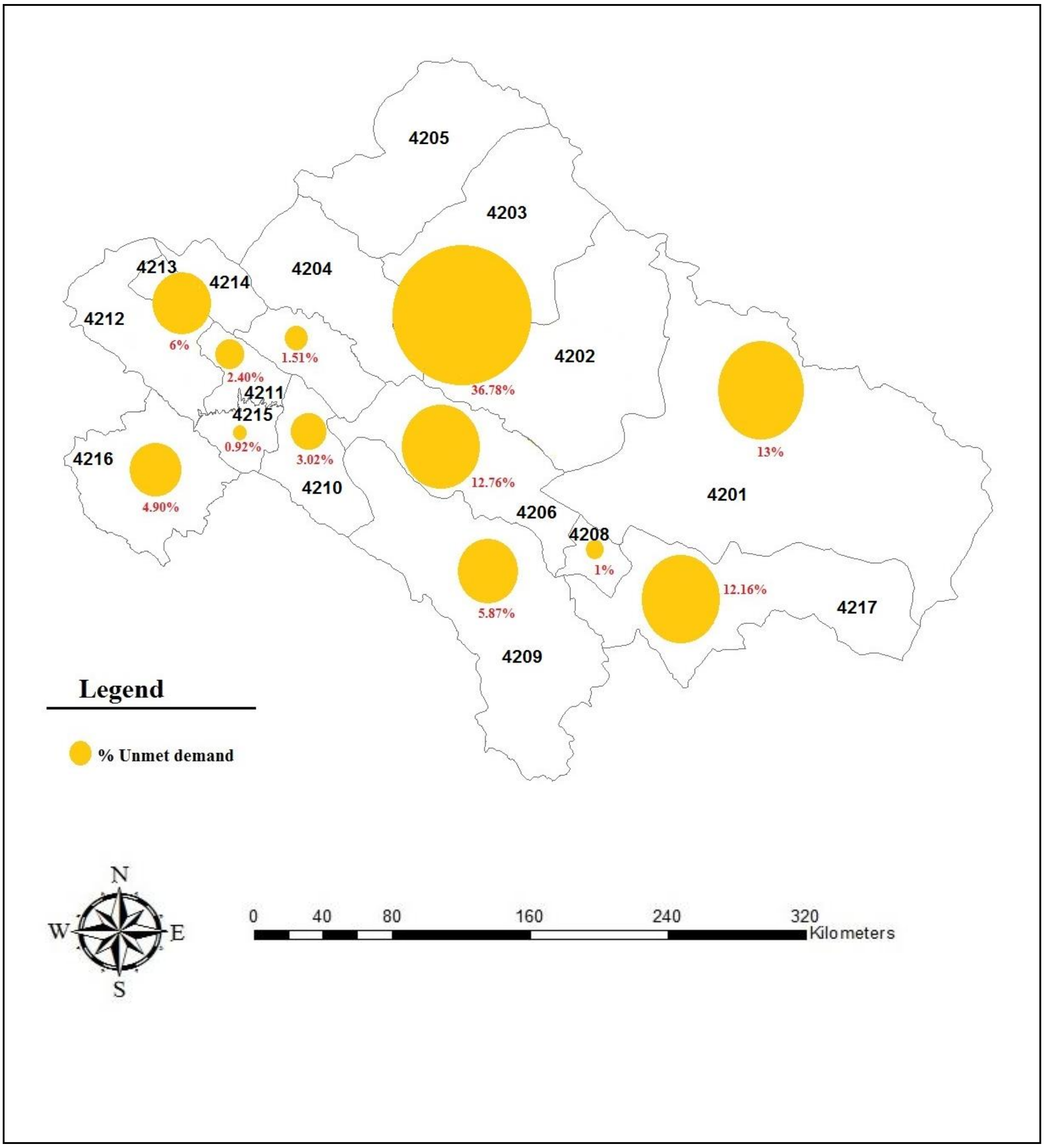


Figure 5.23: Total unmet demands (%) in the sub-catchments

In addition, it is assumed that because of the deficit of stream flow and high irrigation demand, the storage of the Chadegan dam which is the main dam upstream, decreases significantly between August and December especially during drought conditions (Figure 5.24).

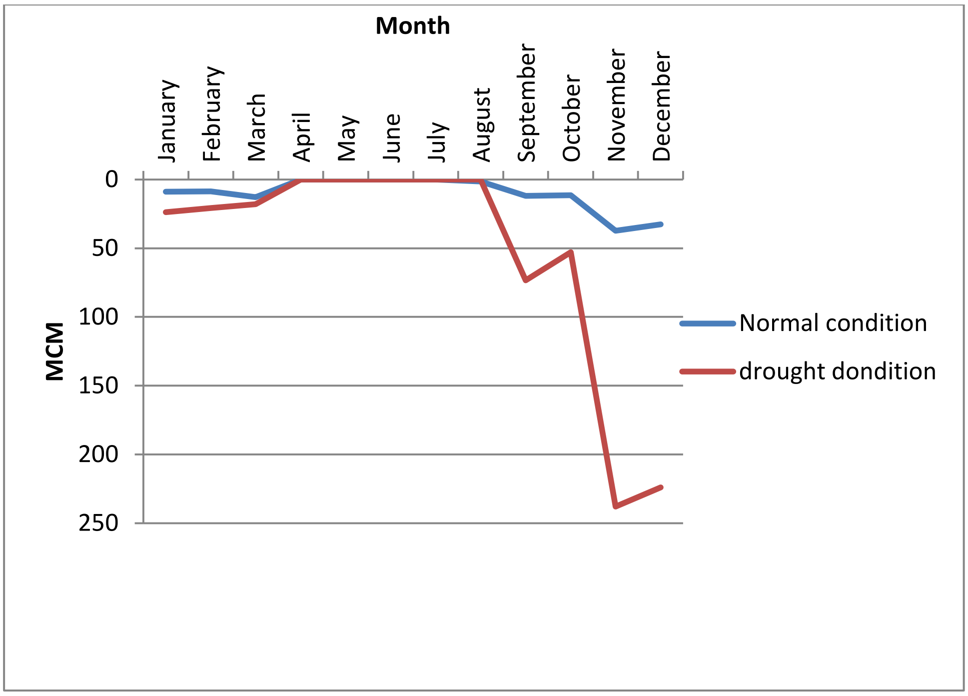


Figure 5.24: Compare decrease in storage of the Chadegan dam in the reference and drought scenario

The reliability of the system is calculated in the WEAP model by the equation below:

Reliability= $\frac{(\text{Number of months which demands are covered})}{Total\ months}\times 100$

The reliability of the system to cover the demand requirements for different scenarios is shown in Figure 5.25. The figure represents the reliability of the water supply to cover all demand requirements is not sufficient. The reliability of the system has decreased during the drought scenario (between 2% to 15%). The highest decrease has occurred in the sub-basins of 4207, 4208 and 4217, which are located downstream. However, in the sub-catchments 4211, 4212, 4215 and 4216, because they are upstream with lower water demand requirements, the reliability has decreased only between 2 to 5%.

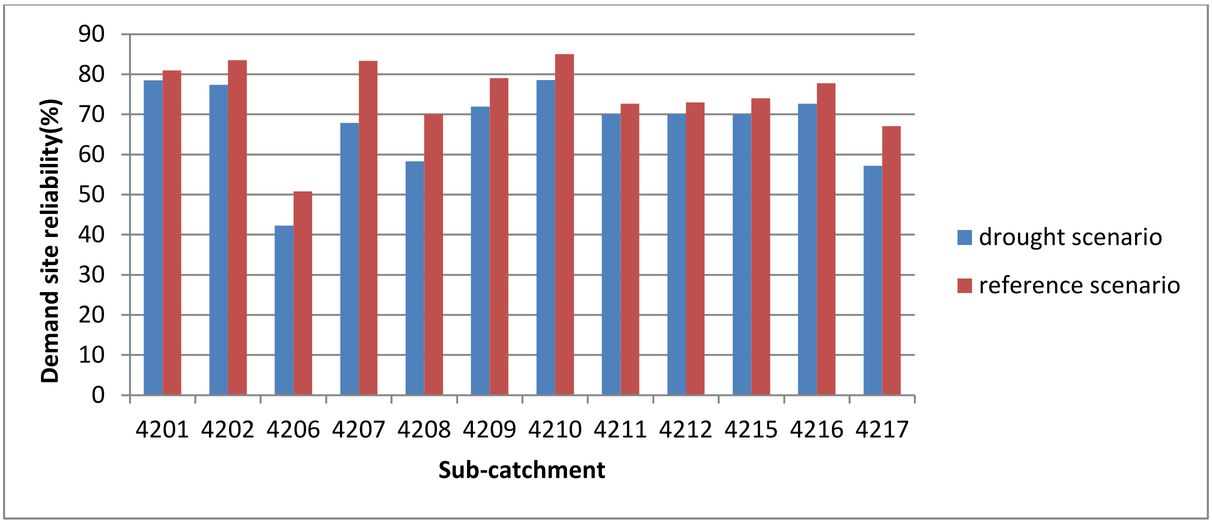


Figure 5.25: Comparison percentage of reliability of the system for demand site in the reference and drought scenarios

5.4.6 The human impact on water supply in reference and drought condition

With simulation flow taking water demands into account in WEAP and compare with measured flow data from gauging stations, it enables to say how water demands mainly impact the runoff the catchment.

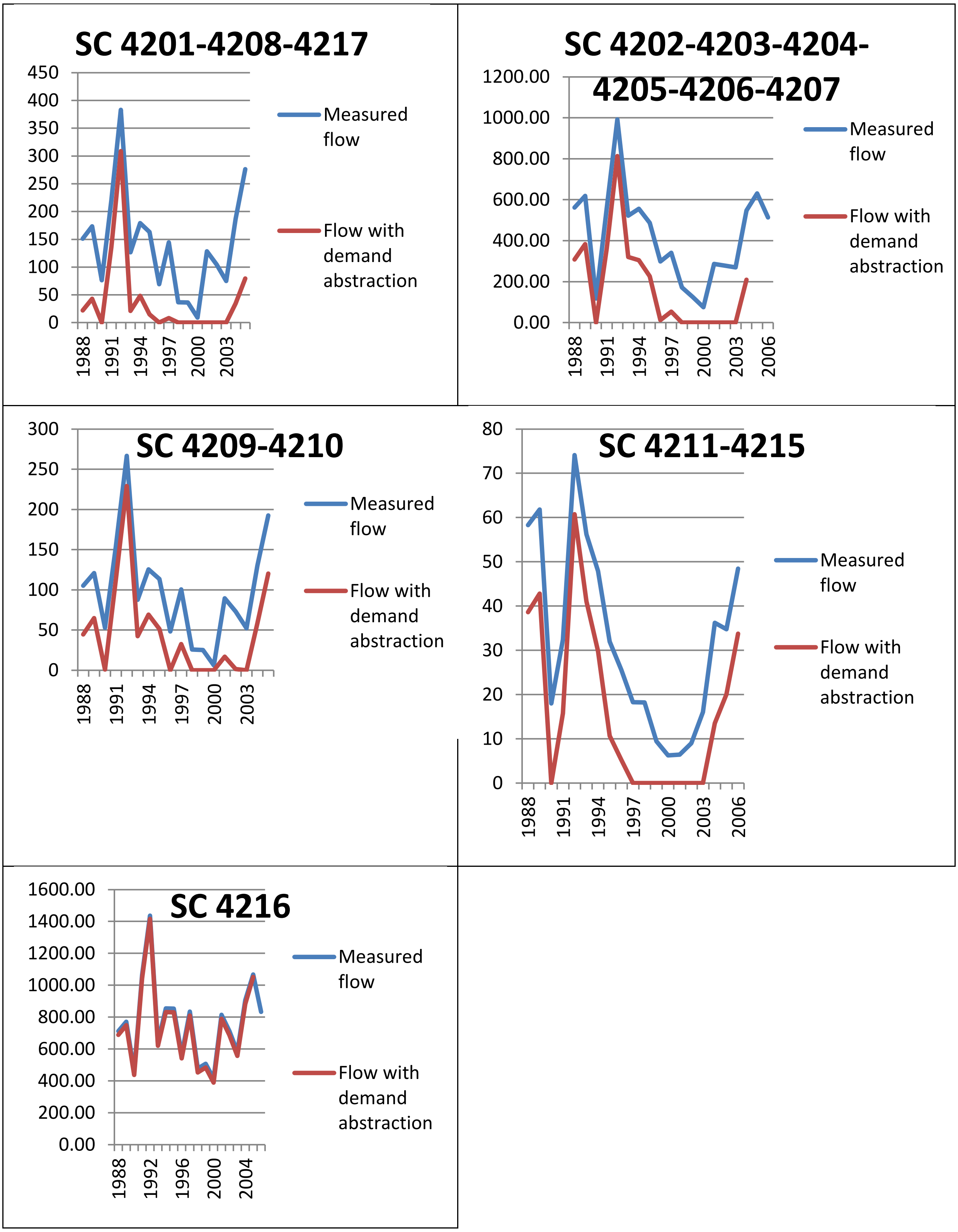


Figure 5.26: Comparison measured flow and flow with demand abstraction during 1988 to 2006

Figure 5.26 indicates how humans impact on the flow reduction by the abstraction of water. The figure also shows that during dry years, the flow became near zero. Figure 5.27 shows that the sub-basins 4202, 4203, 4204, 4205, 4206, and 4207 have the highest reduction, especially during drought period, as the highest demands also belong to these sub-basins. However, the lowest flow reduction is in 4211, 4215 and 4216 which are upstream and in high elevation; they attain more flow because of either precipitation or snow melting. Also, because the water demand is too low in these sub-catchments, especially in 4216, the probability of significant reduction in flow is low.

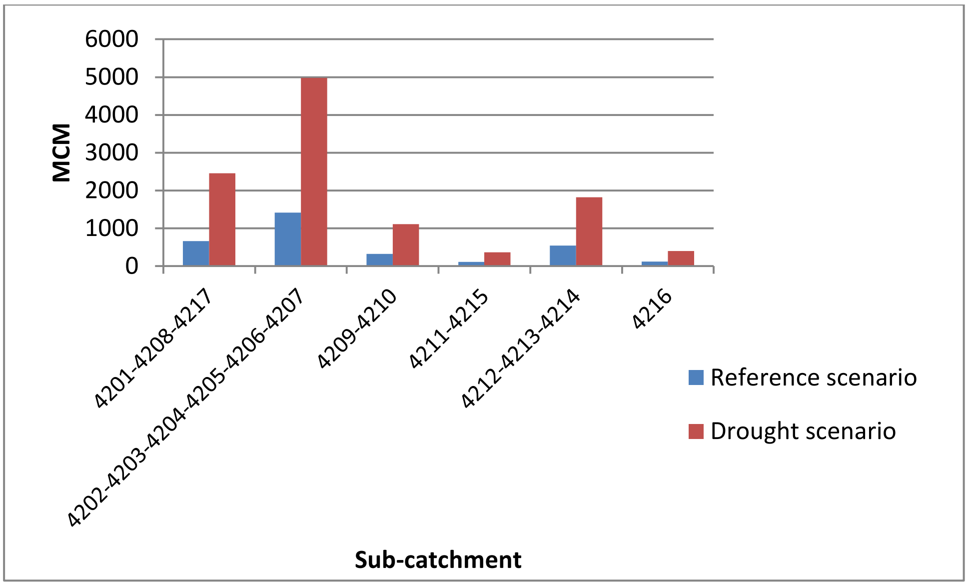


Figure 5.27: Sum reduction of flow after human abstraction during reference and drought scenario in the sub-catchments

Also, Figure 5.28 mapped the total percentage of reduction of flow after human abstraction during drought scenario

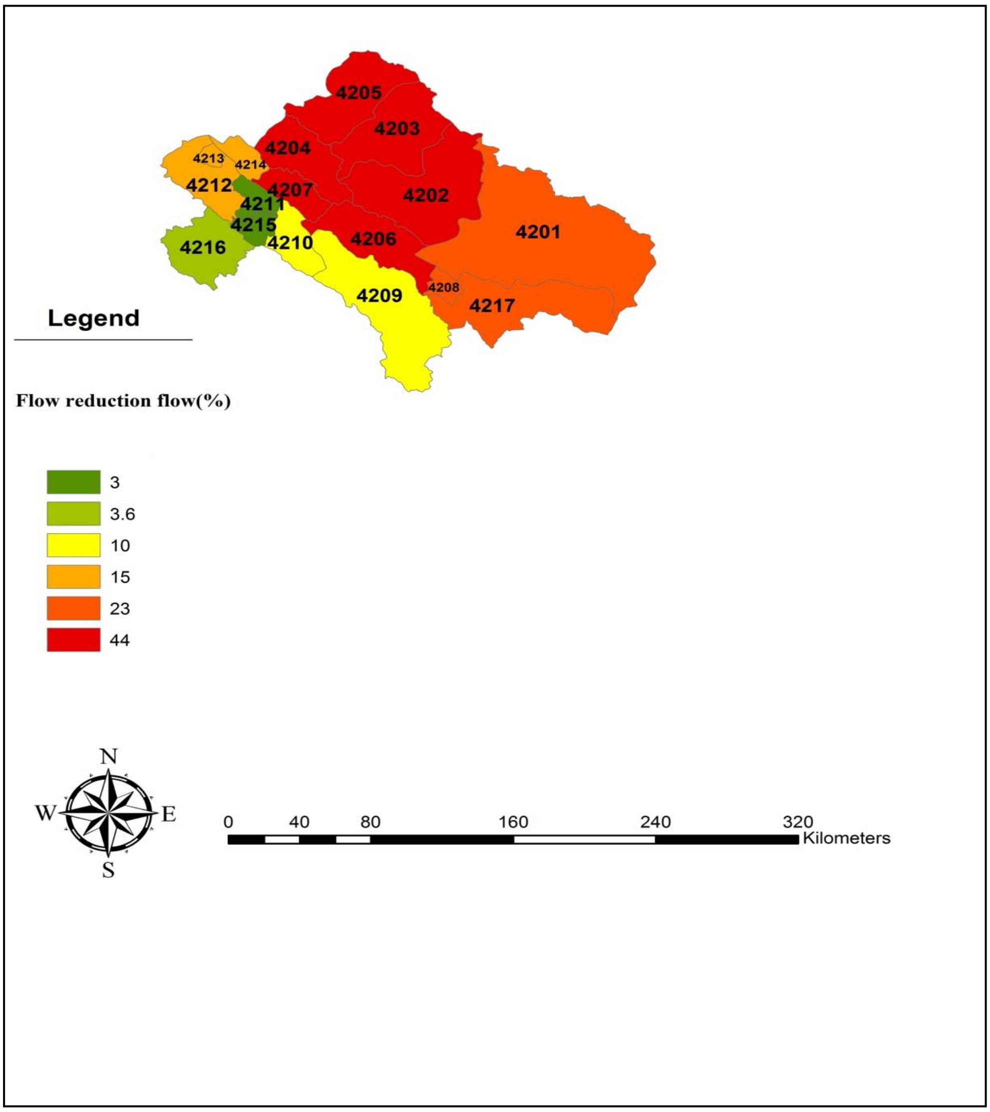


Figure 5.28: The total percentage of the reduction of flow after human abstraction during drought scenario

Furthermore, Figure 5.6 in appendix shows that for all the sub-catchments, the reduction of flow which includes human abstractions occurring creates a worse effect during a drought period.

5.4.7 Socio-economical impact assessment of reference and drought scenarios on agriculture

The main aim of this section is to assess the socio-economic impacts of a drought event on agriculture, which is the biggest water user in the basin. To do this three indicators (number of farmers, crop production and income by crop production) were obtained, and they are shown in Figures 5.29, 5.30, 5.31 and 5.32.

First the strongest drought event and driest years, identified by the z-index in Chapter 4, were selected for the drought scenario. The census data for the population of farmers and data from the Ministry of Agriculture-Iran for crop production and agricultural income for the reference and drought scenarios were specified. Hence, the statistical correlation coefficient between drought index and farmer population, crop production and income were used to determine the socio-economic impact of drought in the sub-basins.

Figure 5.29 represents that generally in all sub-basins the population has grown even during drought periods. The most number of farmers (about 500000) were affected by drought in the 4202, 4203, 4204, 4205, 4206 and 4207 sub-basins, which are located in the middle of the Zayandeh Rud basin; probably because of the large areas under cultivation in those sub-basins. The second greatest population who were affected by drought belongs to sub-basins 4201-4208 and 4217 which are downstream of the river.

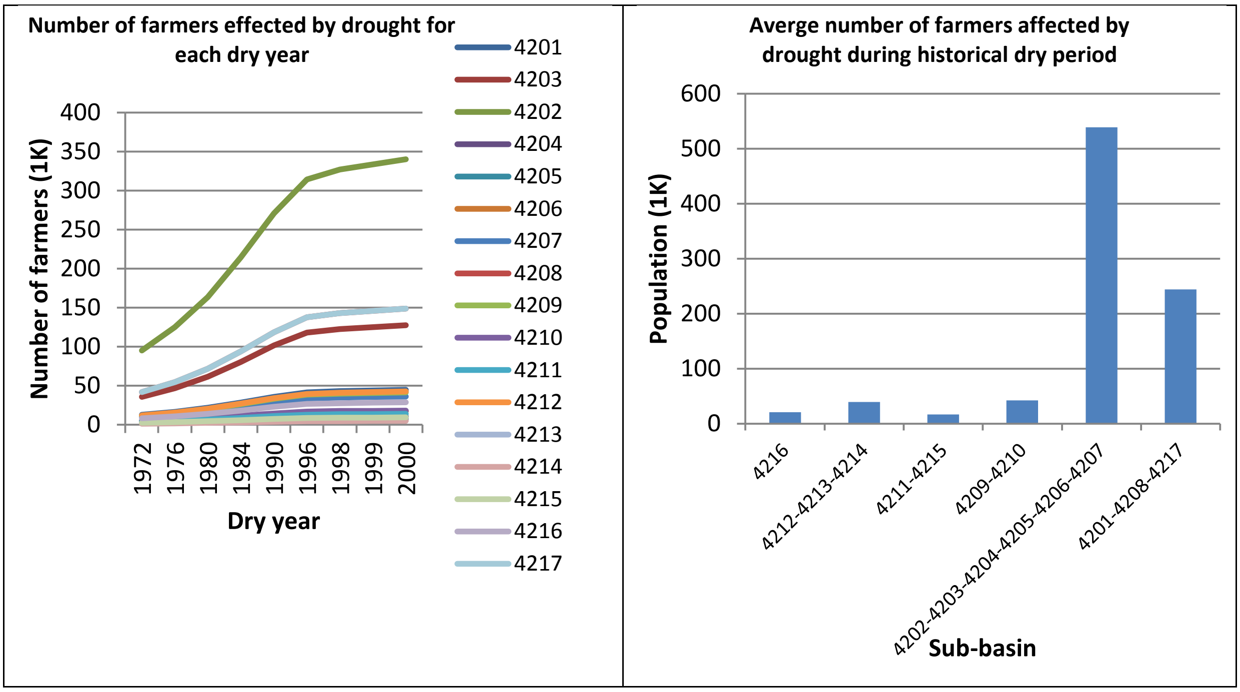


Figure 5.29: Number of farmers affected by drought for each dry year in left and an average number of farmers affected by drought during the whole historical dry period.

Comparison of crop production under the reference and drought scenarios shows that the largest area under cultivation is in the sub-basins 4201, 4208 and 4217; however, the biggest crop production loss happened in the 4202, 4203, 4204, 4205, 4206 and 4207 sub-basins. Figure 5.30 estimates 439960-ton production in 36879 hectares was lost during the drought scenario, as the irrigation efficiency (Chapter 4) is lower, and irrigation demand is higher (because of more cultivated rice) in the 4202,4203,4204,4205,4206 and 4207 sub-basins. The lowest production losses for the 4216, 4211 and 4215 sub-basins were because the area under cultivation, due to their topography, is very small. Therefore, these sub-catchments have the least irrigation demand and their crop production during the drought period is affected less than in other sub-catchments. In the sub-basins 4212-4213 and 4214, because the irrigation efficiency is only 28% (Chapter 4), therefore the irrigation demand is higher, and crop production loss is higher than for sub-catchments 4209 and 4210.

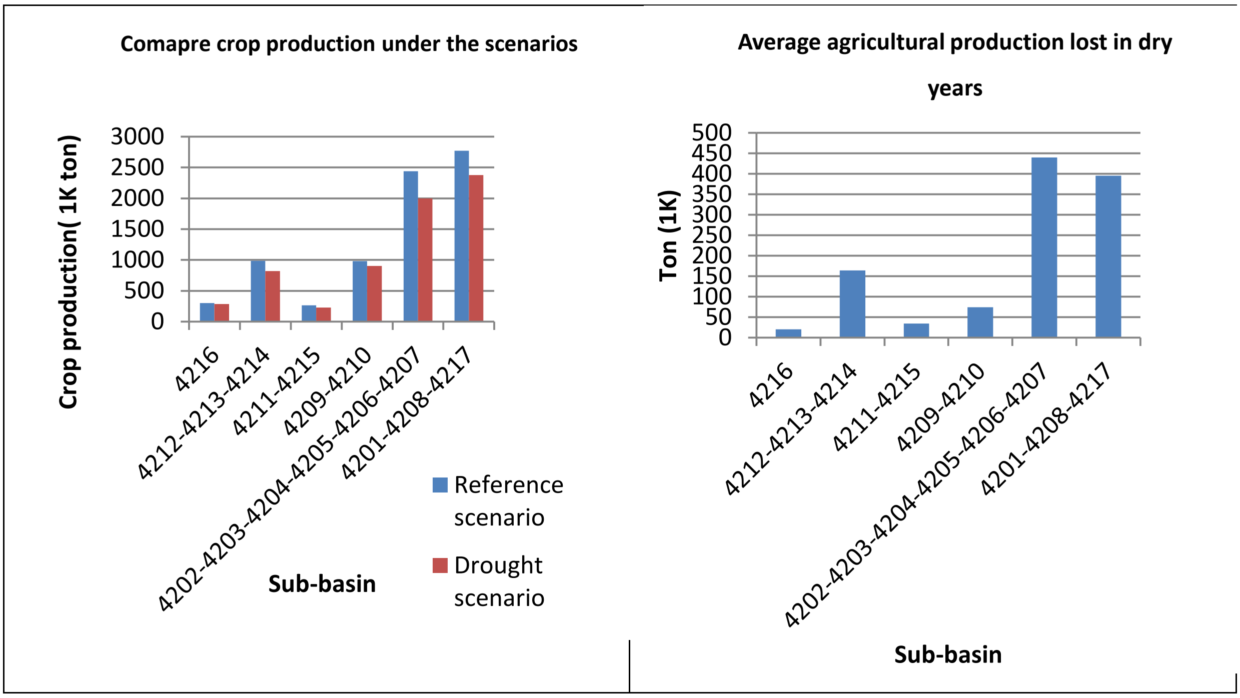


Figure 5.30: Comparison crop production under the reference and drought scenario in left and average agricultural production lost in dry years in right

Figure 5.31 mapped the crop productions lost in percentages in the sub-catchments. The figure indicates the sub-catchments located in the east part of the catchment and also from upstream to downstream more crop productions were lost.

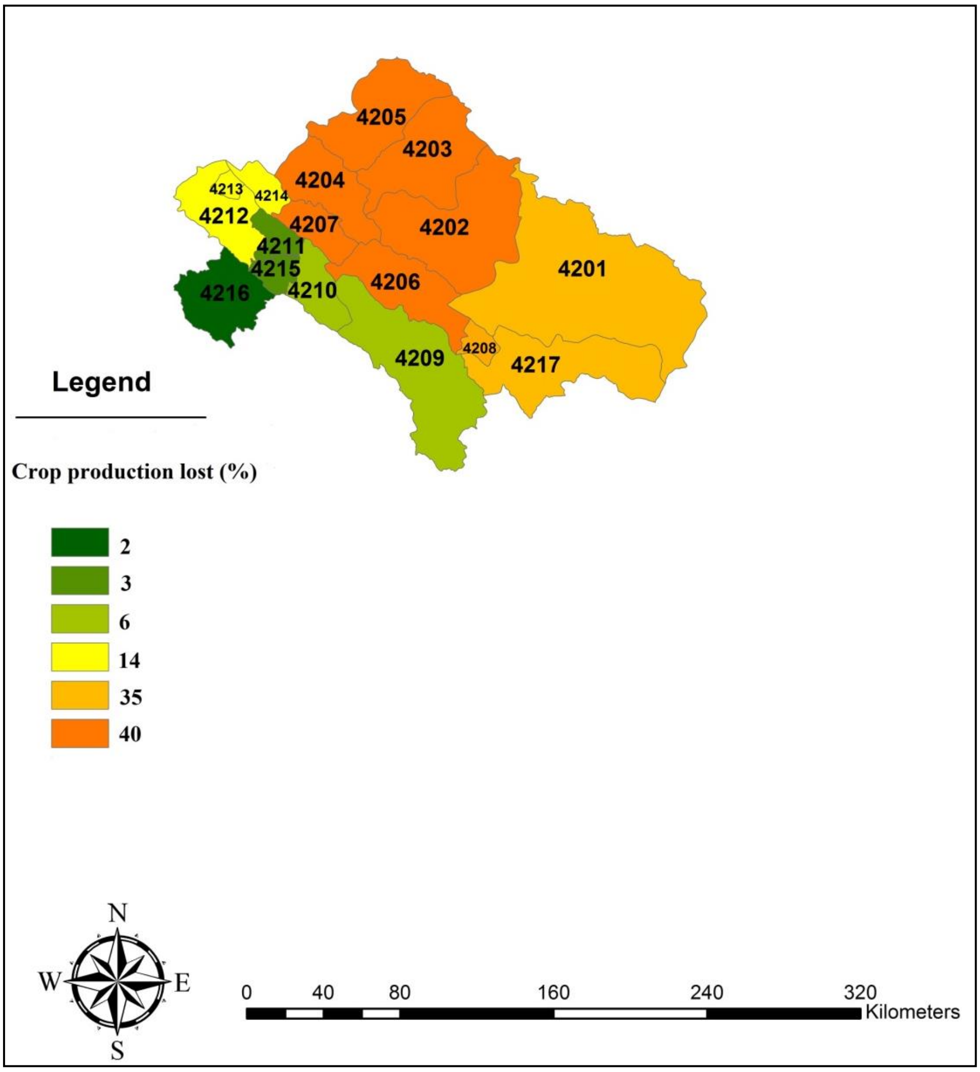


Figure 5.31: The percentage of crop production lost during drought scenario

Figure 5.32 shows that according to the production lost, also the biggest agricultural income, approximately 96.42 million dollars, was lost while the drought period occurred in the sub-catchments 4202, 4203, 4204, 4205, 4206 and 4207. The next greatest income loss is about 95.02 million dollars in the sub-catchments 4201, 4208 and 4217. However, the lowest agricultural income was about 2 million dollars in the sub-catchments 4211, 4215 and 4216.

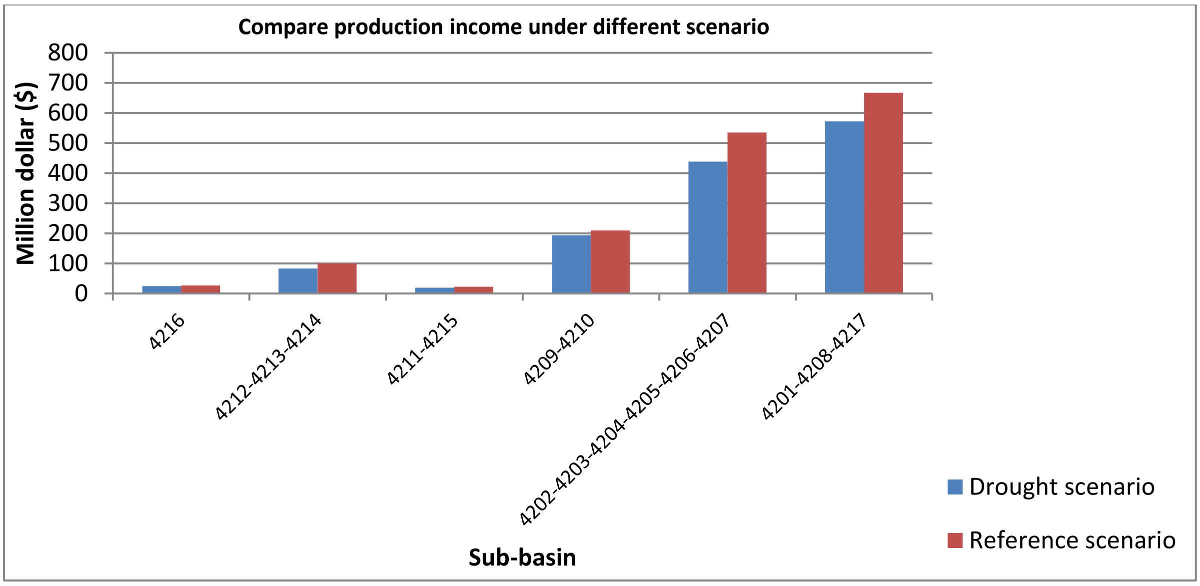


Figure 5.32: Comparison production income under the reference and drought scenario for the sub-catchments

The findings of the correlation coefficient test (Spearman test) indicate a meaningful relation between drought intensity (drought hazard which identified in Chapter 4) and observed data of: cultivated area, the number of farmers, crop production, and agricultural income for dry years (Table 5.7). The result shows that production of cultivation and agricultural income in all sub-basins, are two main factors that are influenced by climatic extremes and drought events; for example in the 4202, 4203, 4204, 4205, 4206 and 4207 sub-catchments. The correlation coefficient between drought intensity and crop production and agricultural income is 0.92 and 0.86 with the significant level of 0.02 and 0.05.

Furthermore, in all sub-catchments, the positive value for the correlation coefficient between areas under cultivated and drought intensity shows that even during the strong drought event, the farmers in the basin did not stop extending areas under cultivation.

Based on the results, we can claim that the strong drought events in 1972, 1976, 1980, 1984, 1990, 1996, 1998, 1999 and 2000 (which identified in Chapter 4) affected the economy after the meteorological and hydrological droughts. The drought scenario based on dry years which calculated by drought indices for observation data of precipitation and streamflow in Chapter 4. Drought impacts have changed the economic and social conditions of the agricultural environment (during the same dry years). The unpleasant social and economic impacts in the region need attentive and long term plans. Therefore providing mitigation plans to decrease the social and economical impacts of droughts is compulsory.

Table 5.7: Comparison correlation coefficient between drought intensity and cultivated area , the number of farmers, crop production and agricultural income in the Zayandeh Rud sub-basin.

Parameter	Test	4216	4212-4213-4214	4211-4215	4209-4210	4202-4203-4204-4205-4206-4207	4201-4208-4217
Area under cultivation	coefficient correlation	0.3	0.39	0.3	0.48	0.57	0.66
	sig	0.4	0.9	0.41	0.9	0.17	0.41
Number of farmers	coefficient correlation	0.25	0.5	0.52	0.32	0.82	0.64
	sig	0.55	0.16	0.14	0.39	0.006	0.05
Total production of cultivation	coefficient correlation	-0.44	-0.65	-0.4	-0.69	-0.92	-0.96
	sig	0.9	0.13	0.15	0.18	0.024	0.01
Farmer income	coefficient correlation	-0.42	-0.66	-0.38	-0.6	-0.86	-0.88
	sig	0.93	0.13	0.15	0.17	0.05	0.01

5.5 Discussion

5.5.1 Approach, assumption and improvement of water allocation

Modelling the hydrological processes and the response of a 42000km2 catchment is a complicated assignment and the results output of the simulation need some caution. Errors in the model come from the structure of the model itself and from the datasets that are applied to run it. Some of the assumptions of the study are reviewed here.

The use of the simple system has some difficulties. Firstly the simplified equations may make some errors which originated from the model structure itself (Beven, 1989).

The catchment response to rainfall is related to different parameters (e.g. intensity and duration). Nevertheless, the model does not count them, unlike some other rainfall-runoff models for example USDA-ARS Riesel Watersheds in Texas(Allen et al., 2011).

Alternatively, the model averages several possible responses of the catchment to provide a link between rainfall and response, which is only based on volume

The second issue is catchment-averaged parameters (e.g. crop coefficients, hydraulic conductivity) will not show the spatial changes that can happen in natural conditions. This issue has not been considered in previous investigations, such as in Sacramento Basin California (Joyce et al., 2011).

Different assumptions also had to be considered in the data estimation as a result of the insufficient data. Although this is a difficulty that has to prevail in many hydrological studies, the catchment area was enormous and measurement of the data by a field study was not possible.

Results of the simulation represent that the main bias depends on water demands. So it is supposed that the quality of the simulation can be improved by:

1) Determining better values of crop coefficients. As evapotranspiration is the biggest water consumer in the catchment, measurement of evapotranspiration is necessary for determining water resources. In the Zayandeh Rud basin, land use types are from different data sources. Such as the Regional Water Authority and Moshaver Yekom Water Authority in Esfahan, so it was difficult to measure average crop coefficients for each sub-catchment with good confidence.

2) Improving accuracy in the spatial and temporal patterns of water demand. Demand data was available simply for the period of 1988 to 2006; in this research, most of the demand was assumed to have varied linearly during the period of simulation. So

providing and applying longer historical census data to determine changes in demands would enable better measurements of temporal patterns in demand.

3) Developing dam operating rules which are based on current dam operations in terms of minimum releases, flood control and stability during the period of low flow.
4) Developing datasets for the aquifer is required. Many of the data required for the aquifer design in the model are not available, and only the largest and the most important aquifer in the Zayandeh Rud basin was simulated in the model.

5.5.2 Water evaluation and planning system

WEAP was selected because as an integrated model it can represent multidimensional processes related to drought as an extreme event of climate change, water resources and water management. Also regards to the spatial scale of this study (basin scale), physical data availability, knowledge level and time availability for this study, the WEAP is suitable to simulate water allocation. Furthermore, it operates in a simple manner. The goal was not to examine the hydrological process of the Zayandeh Rud basin accurately; but, to be capable of simulating the water resources and water demands of the basin with limited data and to use fewer parameters.

The results of the simulation enable a natural flow time-series to be made from rainfall data. Sensitivity of the model which is not considered in previous studies (Rochdane et al., 2012, Purkey et al., 2008) shows that only effective rainfall has significant impact on the mean annual flow; so effective precipitation may have great impact on the model efficiency. Unlike other water allocation models, such as the MODSIM model in the Awash river basin in Ethiopia (Berhe et al., 2013), our results indicates WEAP can simulate human abstractions with some accuracy and could be applied as a planning or policy analysis tool. The calibration and validation results (e.g. EFF and r-squared values) indicated that the model performs fairly well.

There are some limitations in the application of the model:

Calibration of the rainfall-runoff component of WEAP was done manually as no optimisation routine was contributed.

The WEAP model is time-consuming; since it has to be set up for each run.

An important development for the user would be the establishment of an optimisation model in WEAP, to give an output set of parameters that optimise one of the efficiency criteria.

Although automatic calibration procedures make some errors in parameter measurement due to the selected optimisation algorithm or the calibration data (Gan et al., 1997), it can save time for users.

5.5.3 Output of the model

The WEAP system provides the planning tool for water resource management as it can analyse:

- Impact of the drought and climate change
- Impact of the hydrological structures on the river flows
- Impact of the change in water demand over time
- Impact of the allocation rules of upstream/ downstream
- Impact of the setting up of the ecological reserve

Evaluating the Chadegan Reservoir storage indicates that the reservoir does not always receive adequate flows to supply full irrigation demands.

The analysis of the results shows that despite the shortages in the flows (occurring due to supply inadequacy and drought conditions), the water demand was increased especially between August to December, and severe drought also occurred during these months.

Generally in the basin, because of high water demands for irrigation the system operates in a failure risk range that was obtained by unmet demands for both reference and drought scenarios. Also the current irrigation infrastructure and irrigation techniques provide much more water losses, especially in the 4202, 4203, 4204, 4205, 4206 and 4207 sub-catchments (see Figure 5.24). The lack of implementation of rules or control methods for limiting water uptake in those areas increases the exposure of the water supplies. So, the value of “reliability of supply to deliver water to demand site” indicated the current situation of water management is not fair enough to cover water demands especially during dry periods (Figure 5.27).

Most of the previous studies (for example Dirsen and Taylor (2003), Juana et al.(2012)) only focused on direct effects of drought on water demands, however, they did not estimate adequately a range of socio-economic impacts of drought on the water demands. The methodology in this study has evaluated the socio-economic impacts of drought by four indicators and it demonstrates how the numbers of farmers in each sub-basin were affected by the water deficit. The study confirms the previous study of (Fischer et al., 2005); that the socio-economic impacts of drought are significant in the developing the world. In this research, unlike previous research on drought hazard impact on cultivation in Iran (Mansouri Daneshvar et al., 2013), the positive value for the correlation coefficient between areas under-cultivated and drought intensity shows that even during the strong drought event, the farmers in the basin did not stop extending areas under cultivation. However, the high coefficient correlation value shows that the production of cultivation and agricultural income in all sub-basins are two main socio-economic factors that are influenced by climatic extremes and drought events.

As a consequence, WEAP can be used as a management tool. The results of this chapter show that alternative management is needed to prevail over future drought impacts. The potential adaptation scenario in terms of future drought characterization as (Mukheibir, 2008) and (Xiao-jun et al., 2012) suggest will be:

1) Permanent reduction of agriculture water demands

2) Increase in water regulation capacity by construction of a new dam

3) Upgrade irrigation techniques and crop diversification.

5.6 Conclusions

The main conclusions derived from the results and process of this chapter are summarised here.

The results show that WEAP can simulate well the naturalised flow time series, and has the ability to model the rainfall-runoff response of the catchment. Also, the results from the water allocation simulation revealed that WEAP is an effective tool for the estimation of water resource development and management demand in the basin.

In this study generic modelling software based on the network flow algorithms' computer-based simulation model successfully evaluated the socio-economic impacts of drought.

There are a few studies that deal with water resources' assessment and impact of development and also analysis of different scenarios (e.g. reference and drought scenarios) at the scale undertaken in the current study. However, this is a crucial step in water management (especially with the creation of drought management and water management agencies) to be reached on this scale.

The water allocation model of WEAP is crucial for understanding water demand and the behavior of water users and provides meaningful results of policy making using socio-economic indicators (especially for critical period of drought). Analysis of irrigation water demand shows that there is an important increase of water requirement during dry years, making additional stress on the water supply system.

These increases should be considered in the development of water supply management systems to mitigate the impact on crop production.

The investigation of water demands' variations is interesting since the potential to choose alternative crops applicable to the water availability in the system in the long term will be defined. In this case, the analysis of the reference scenario, which includes normal conditions, can make a range of options that farmers can adopt in case of drought. Also, it would be effective as a general land use planning tool to obtain the most applicable crops to the conditions of the basin. Because especially the risk posed by drought and the impacts as well depends on farm cropping and technical characteristics, water management and decision made in irrigation areas (as mentioned in Chapter 4).

The drought impact will be more significant on those systems that are currently performing on a failure risk (which are identified by unmet and reliability values in the results). These systems will require management adjustment for average conditions in the future. However for those systems which work on lower failure risks currently, probably the present management would be sufficient for the average conditions under climate change and drought. For example, in the sub-catchment 4202 the unmet demand is high and reliability of the water supply to deliver water to demand sites was lower than in other sub-basins even in the normal conditions.

To analyse the integrated water management model (WEAP) the monthly time step was applied. It provides the opportunity to adapt management options along the hydrological year as stated by evolution of drought determination indicators, developing the response capacity for drought events and mitigate the potential impacts of drought on the environmental, social and economic aspects.

Furthermore, the analysis of the results indicates the effect of the seasonality of drought events for the decision assessment process. As hydrological droughts are developing and also there are high agricultural demands during autumn and summer, the response period is longer, so adaptations plans in agricultural demand would be useful to decrease the impacts of drought. Therefore, the application of a decision support tool which is applied in this chapter is necessary for determination of any kind of drought event or variable in environmental conditions that can influence water resources availability.

In summary, this research has contributed to support water management and policy making by estimating impacts of drought on: water supply, unmet demands and reliability of water resources to deliver water to demand sites. Also this study has highlighted and extimated the relevant aspects of socio-economic parameters that can shape the risk posed by drought.

CHAPTER SIX: THE IMPACT OF FUTURE CLIMATE CHANGE AND HUMAN WATER ABSTRACTIONS ON HYDRO- CLIMATOLOGICAL DROUGHT , ANALYSIS AND PROJECTIONS : USING CMIP5 CLIMATE MODEL SIMULATIONS

6.1 Introduction

Droughts continue to be a significant natural hazard, around the world and specifically in arid or semi-arid areas like Iran. Recently 10 out of the 28 provinces (35% of Iran) were affected by several droughts (Raziei et al., 2009). The most costly drought disaster was in 1999, with an estimated loss of $1,605 million (Salami et al., 2009).

Increasing evidence of global warming is followed by a pressing question: will climate change exacerbate the risk of drought at a regional or local scale?

Recently, according to the Fifth Assessment Report produced by the Intergovernmental Panel on Climate Change (IPCC), droughts have become stronger and longer and have influenced larger areas since the 1970s (Core Writing Team, 2014). The land area (Iran) affected by drought is supposed to expand and so availability of water resources by mid-century could decrease as much as 30% (Abbaspour et al., 2009).

Climate change can explain any alteration in climate over time, either because of natural variability or due to human activity. These changes can cause alterations in the statistical properties of distribution of the variable investigated, as changes in their mean values or variability in a specific range of values. Alteration in precipitation variability may cause more frequent and detrimental extreme events such as drought (Penalba and Rivera, 2013). Climate change is anticipated to affect the frequency and severity of droughts principally. Most of the research in Iran focuses on changes in the mean of the climate (Sayari et al., 2013) rather than in changes in individual temporal which is important in drought characterisation. Also no work proves the occurrence of future trends in precipitation and runoff at different time scales over the central area of Iran. Therefore, influences of climate change on drought characterisation remain unknown. Although, General Circulation models (GCMs) have been improved for the application of modelling the earth's climate, still there is uncertainty in the climate projections which are required to determine drought risk (Ban, 2007). The GCMs have complex mathematical formulations in order to explain how the climate works and how it would change if main factors of climate disturbances are known.

The difficulty lies in the fact that GCMs which are applied to project global climate change cannot determine the main factors of climate disturbances sufficiently that are likely to have effects on regional climates (Arnell and Lloyd-Hughes, 2014).

Furthermore, the reliability of model outputs for extreme events at large scale is not as good as for climate averages at small scale. Several methods have improved downscaling precipitation from GCMs (Wang et al., 2011a, Maraun et al., 2010).

A few studies, such as (Burke and Brown, 2008) defined the impact of climate change on worldwide drought on the basis of multiple drought indicators including SPI, potential evaporation anomaly, soil moisture anomaly and Palmer Drought Severity Index. However there is a lack of research, which includes uncertainties of regional climate change into drought risk evaluations at the local level.

Even in the research at continental scale, there is uncertainty in the selection of GCMs. For example the study of (Kirono et al., 2011) is an example of drought characterisation in Australia which applied climate variables from 14 GCMs which just were selected randomly from the IPCC 4th assessment report.

The research of Dastorani (2011) is another example of evaluation of potential impacts of climate change on SPI and RDI for the period of 2010-2039 in the west of Iran, which applied data of one GCM-run, selected randomly from the Third Assessment Report (TAR) based on the IPCC SRES scenarios. However, no study has focused on the future changes in drought risk in the centre of Iran based on analysis the CMIP5 models, which is essential for improvement planning for water resources and demand management. TheCMIP5 can simulate a standard set of models in order to:

1) Evaluate how realistic the models are in simulating the recent past.

2) Make projections of future climate change on two time scales; near term (out to about 2040) and long term (out to about 2100).

3) Understand some of the factors responsible for differences in model projections, containing quantifying some key feedback such as those including clouds and the system of atmospheric carbon cycles.

The Zayandeh Rud basin (Figure 6.1) is important in central Iran where agriculture is the dominant activity. The important crops are rice, wheat, potatoes and barley. About 90% of the basin's land use is dedicated to agriculture. Also, one major urban area, the city of Esfahan, is located in the basin. Recently there are increasing competing demands from surrounding agricultural, industrial and metropolitan areas which have experienced water scarcity and strong droughts several times (1972, 1976, 1980, 1984, 1990, 1996, 1998, 1999 and 2000) over the past five decades. However, there is lack of knowledge of the characteristics of drought and predication for future risks in this area.

This work is the first study that applies multiple indices to assess historical and future drought in the basin and for use in future water planning models. Also impact studies of climate change on hydrology at regional scales needs grids or stations at finer resolutions. A method to approach this is downscaling of the GCM data and applying bias correction.

Also the impacts of non climatic factors such as human abstraction on drought are neglected. For example, previous studies in Africa, North and South America and Australia only focused on the direct cause of drought such as climate change (Horridge et al., 2005, Gleckler et al., 2008, Seager et al., 2009, Verschuren et al., 2000, Glantz, 1987, Le Houérou, 1996). Therefore, the aim of this chapter is to determine the future climate change impact on drought and the objectives are:

1. To quantify the range of predicted changes in future climate conditions (precipitation and temperature) and compare them with historical observations from the Zayandeh Rud basin.

2. To assess the contribution of human withdrawals of water versus climate impacts on the future stream flow (runoff) to quantify anthropogenic influence.
3. To determine of the impact of predicted climate change on drought severity, duration and frequency using SPI and SRI as basin scale drought metrics and analyse the relationship between meteorological and hydrological drought indices without adaptation scenarios.

The climate projections are fed into a calibrated water allocation model (WEAP) for the Zayandeh Rud river basin. Then the outputs of the model are applied to determine the impacts of climate change on other water resources, water demands and also crop productions in Chapter 7. Understanding the propagation of climate change impacts by nonlinear water allocation model processes among drought indices could determine the risk behaviours across drought indices, which are analysed in the next chapter.

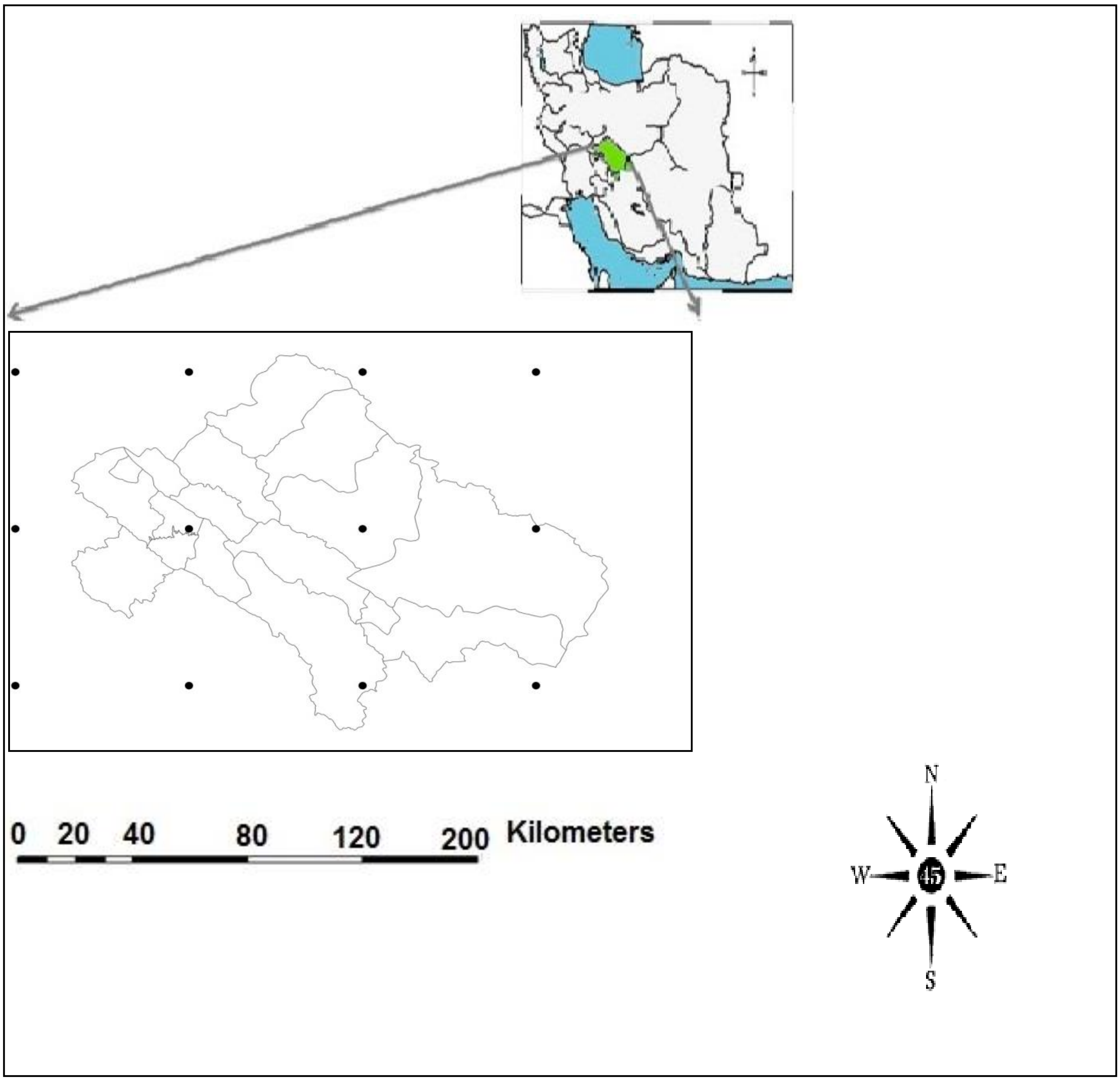


Figure 6.1: Grid points across the Zayandeh rud basin for HadCM3 model

This chapter is divided into five sections:

A description of the data sets for the model and methodology is explained in section 2. In this section, the applied statistical downscaling technique using GCM models with the severest emission scenario (RCP 8.5) is explained to show a spectrum of possible climate projections. According to the method used, recently under the fifth phase of the coupled Model Intercomparison Project (CMIP5) some global circulation models have been developed to deliver long term experiment projections of the “forced” responses of climate to changing atmospheric composition and land cover parameters (Taylor et al., 2012).

Sections 3 and 4 include the results and a discussion on the parameters used for the climate models and also aspects of human abstractions, which increase risk of droughts. The summary and conclusions are shown in section 5.

6.2 Materials and methods

6.2.1 Future climate data

Climate data of the study area have been extracted and modelled for SPI and SRI calculations. For this work data sets applied were the Koninklijk Nederlands Meteorologisch Instituut (KNMI) with Earth System Grid-Program for Climate Model Diagnosis and Intercomparision (ESG-PCMDI) (Williams et al., 2009) which cooperated with observer station data. In addition the National Climate Data Center and World Meteorological Organization participated with KNMI to project the future climate for Iran and the study area. The observational surface temperature (^{O} C) and monthly precipitation (mm/day) data cover the time period from 1971 to 2005 in a monthly time step. Raw projection data are retrieved from the Coupled Model Intercomparision Project phase 5(http://climexp.knmi.nl/help.cgi?id) multi-model dataset (Table 6.1 in Appendix) for the period of 1971 to 2100. CMIP5 includes climatic variables such as temperature, precipitation, relative humidity and wind speed projections under four emission scenarios (RCP) for 2006-2100. To obtain the simulation of climate variables for the meteorological stations, the latitude and longitude of the stations were selected. This gave the simulation points which are the nearest points to the given observation points.

6.2.1.1 KNMI data sets and extraction of the climate data

The Royal Netherlands Meteorological Institute KNMI has conducted and updated the Climate Explorer (climexp.knmi.nl/) since 1999. The Climate Explorer is a web-based application for climatic research, which includes extensive collections of climatic data sets and analysis tools. With free registration, researchers are able to explore and download a collection of climatic data sets, upload their own time series, and provide developed data.

The CE was used for this study: 1) to explore and download available future climate data and derived time series; 2) to determine climate signal in high resolution time series; 3) to apply climatic data to characterize the intensity, duration and frequency of future droughts and manage future water allocation and planning.

6.2.1.2 Exploration of data sets

CE makes climate data sets in the scheme of time series (station data and climate indices) and gridded fields (observations and reanalysis fields). All data sets can be accessed by choosing the suitable time series or fields format on the CE web page. For climatic analysis, monthly time series and fields are most valuable.

By selecting a time series of monthly station data (i.e. precipitation and temperature), CE gives the opportunity to provide a selection based on a station name. In addition a minimum number of years of data availability can be introduced, as well as a range of years for which data may be accessible, and an elevation range. The study searched for the 17 stations nearest to the Zayandeh Rud basin (50^{O} 24' to 55^{O} 24' longitude and 30^{O} 11' to 34^{O} 11' latitude and elevation of 2300m a.s.l) and used a filter of a minimum 30 years of monthly data availability. CE gives the choice to recover data for a single grid point for the area. The raw data were available in column format. Therefore adjusted precipitation and temperature time series data for four stations (with given grid point) which were available were extracted.

6.2.2 Future hydrologic conditions and data

In order to get the future hydrological data (e.g. stream flow), the downscaled climate data (precipitation and temperature) should be used as input in the hydrology model of WEAP.

The total period of simulation is from January 1971 to December 2100, with the first 34 years (1971-2005) having the same station data applied in simulation of historical hydrology by the WEAP model in Chapter 5. The period of future initial climate input data for the hydrological model is from 2006 to 2100. The variables altered to run the WEAP model have been summarized below.

6.2.2.1 Climate variables

The monthly climate variables from a model derivation, summarized in section 6.2.3.2, were made for the basin over the simulation period. MS Excel files were made for the model to read the data.

6.2.2.2 Land use parameters

For simulation of the future scenarios, the Kc remained fixed under the assumption that the current state of land use will remain fixed to 2100. Furthermore, land use patterns are highly dynamic and can be evaluated applying other models such as CLUE-S (www.cluemodel.nl). The runoff/infiltration ratio is calculated using the same method used in Chapter 5. However predicted precipitation values are applied to provide new runoff and new infiltration for each month to the year 2100.

6.2.3 Methods

To assess the potential impact of future climate change on meteorological and hydrological droughts and also effects of human abstraction on the hydrological droughts, the methodology which is used in this chapter is divided into four sections. At first the future climatic model prediction (section 6.2.3.1) which is necessary to provide precipitation data for meteorological drought is explained. The climate model generates the initial data (precipitation, temperature, evaporation, relative humidity and wind speed) to run the hydrological model (section 6.2.3.2 and 6.2.3.3). In section 6.2.3.4 the method which is applied to calculate the intensity of droughts and analysis of the frequency and duration of meteorological and hydrological droughts is presented.

6.2.3.1 Climate change simulations

Generally climate change predictions made by models are not aligned with the 'real' natural environment because of uncertainties and data errors in the models. Recently CMIP5 results tried to fill this gap with a finer resolution for the models and also with new climate change scenarios. In this research different outputs from climate models were utilised monthly output from 38 GCM which participated in the CMIP5 was applied. These new models are more nuanced, more developed vis-a-vis the CMIP3.. In addition to the CMIP5, new models for predicting climate change using different scenarios , such as "Representative Concentration Pathways" (RCP) developed by Van Vuuren et al. (2011) (Van Vuuren et al., 2011) exist. This model can be used to predict GHG mitigation potential. (Hasegawa and Matsuoka, 2012).

Model scenarios applied in this study include historical simulations and future projections. The historical simulations were forced by observed natural and anthropogenic atmospheric composition changes spanning 1971-2005; they are applied to make a baseline against which to determine climate change in future projection. The future projection is obtained by forcing from the RCPs. Unlike the Special Report on Emission scenarios (SRES) that announced the climate projections for the previous CMIP experiment (CMIP3), the CO_2 concentration in RCP2.6 is below B1, in RCP6.0 is a little above A1B, and in RCP8.5 surpasses A2. In this study the RCP8.5 scenario (which is the severest one) is applied for 2006-2100. The severest potential GHG path for the 21st century is selected to make the strongest planning adaptation to mitigate the potential climate change impacts on droughts, supply availability and water demands.

Multiple ensemble members are available for each CMIP5 scenario for the given model. Assuming that there are enough models in the ensemble to approach reliable estimates of a potential climate change signal, in this study only one ensemble from each CMIP5 model (total 38 models) and scenario RCP8.5 is applied. The variables applied are: precipitation, temperature, relative humidity and wind speed. However in the results section only precipitation and temperature, the most important variables, are represented and analysed. The aim of providing 38 coupled GCMs in the scenario of RCP8.5 is to show the uncertainty in climate impacts growing from future climate modelling.

Moreover, biases in climate variables such as precipitation should be taken care of; otherwise they will extend into the computations for subsequent years. Possible sources which cause errors and bias are:

- Partial ignorance about some geophysical processes
- Assumptions for numerical modelling
- Limited spatial resolution
- Parameterization
- Bias on resolved scales
- Additional bias can occur on smaller scales (sub-grid/ station).

In order to solve the resolution problems and possible errors in GCM outputs, they are downscaled statistically to each of the meteorological stations. However, to decrease the model's error and increase the resolution precision we use a simple downscaling technique to increase the accuracy of the model as summarized by Hawkins et al. (2013). Some downscaling techniques attempt to improve daily timescales. In this study, because the drought characteristic analysis cases and water evaluation and planning models are used on monthly resolution, just monthly average climate data are necessary and so resolving the high-frequency variability (the intent of more complex approaches) is not necessary.

In order to remove bias between the GCM and reality, monthly precipitation and temperature time series from GCM and observations for a specific location for the same reference period is needed, which is denoted by $X_{p,\ gcm}$ and $X_{p,obs}$ respectively.

Furthermore, output from the GCM for some future period of the same length as the reference period, $X_{f,\ gcm}$ is needed. The question remains about how to best combine these three source of information into the most robust projections of the unknown future observations $X_{f,\ obs}$ to use as input for the hydrology model (WEAP). This study considered a general approach namely change factor. This is similar to delta change methods used for weather generators. However, the approach taken here is simpler, as a shifted and scaled version of the observed time series is applied for the future rather than a series taken from a weather generator.

The change factor methodology uses the observed monthly variability and changes the mean and monthly variance as simulated by the GCM (Arnell et al., 2003). In the simpleset case this is the "delta method", where the monthly variability is assumed to have the same magnitude in the future and reference periods, and the corrected monthly data is,

$X_{DEL}(t)= X_{p,obs}(t) + (\bar{X}_{f,\ gcm} - \bar{X}_{p,\ gcm})$ **Equation. 1**

Where the time mean is denoted by the bar above a symbol and the result of the bracket ($\bar{X}_{f,\ gcm} - \bar{X}_{p,\ gcm}$) known as climate signal which shows in Figure 6.2.

However, in a more general case, considering changes in variance, is (Ho et al., 2012),

$$X_{(f,obs\ m,y)} = \left[\bar{X}_{f,gcm_m}\right] + \left[\bar{X}_{p,obs_m} - \bar{X}_{p,gcm_m}\right] \times \left[\frac{\bar{\sigma}_{f,gcm_m}}{\bar{\sigma}_{p,gcm_m}}\right]$$ **Equation. 2**

$X_{(f,obs,m,y)}$ represents the unknown future observations value of variable X for a given month, m, and period of years, y. The variables contain temperature, rainfall, relative humidity and wind speed; $\bar{X}_{f,gcm_m}$ indicates the mean future simulation for a specific month and period of years (such as 2006 to 2040). $\bar{X}_{p,obs_m}$ is the mean present-day observed climate for a specific month averaged across all years of the historical period (1971-2005), as measured from the meteorological stations in the study area; $\bar{X}_{p,gcm_m}$ indicates the mean simulation from GCM for a specific location for the reference period (e.g. 1971-2005); $\bar{\sigma}_{f,gcm_m}$ and $\bar{\sigma}_{p,gcm_m}$ represent the standard deviations of the raw model output for the future and present-day period for a specific month. The ratio of $\frac{\bar{\sigma}_{f,gcm_m}}{\bar{\sigma}_{p,gcm_m}}$ is shown in Figure 6.3

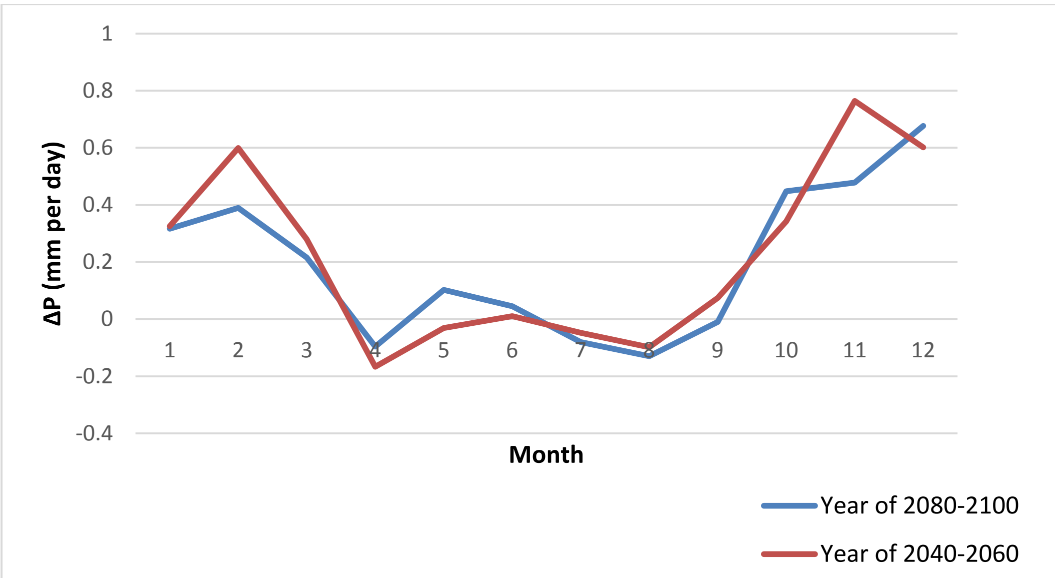


Figure 6.2: Monthly climate change signal for HadCM3 model

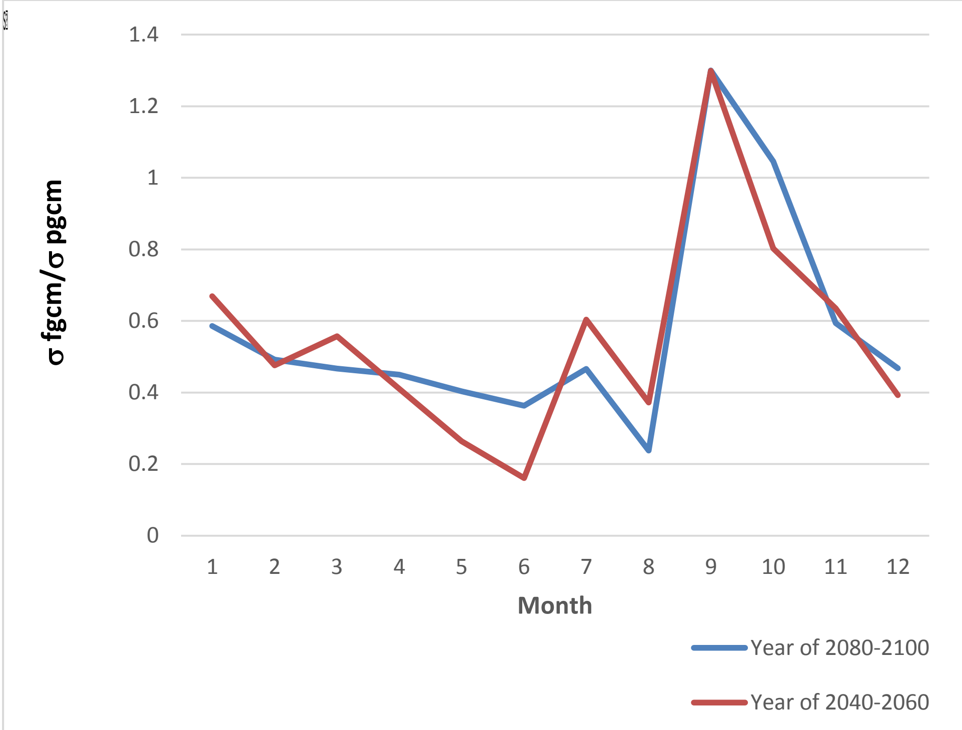


Figure 6.3: Monthly ratios between future and present mean standard deviation of precipitation for HadCM3 model

Figure 6.4 shows precipitation anomaly relative to the monthly mean for all models for 1971-2005 (bracketed term 2 in equation 2). The figure explains to what extent the biases in the mean are seasonally dependent. The figure indicates variability in precipitation anomaly between the models for each month. Some models show negative and some of them represent positive precipitation anomaly. The models which show small anomaly for winter and spring (the seasons which mostly drought occur) can better match with observation data. Generally, it seems for all models during the summer period (June to September) the anomaly is less compared to other seasons. In this figure model HadCM3 has the least difference from the observation data.

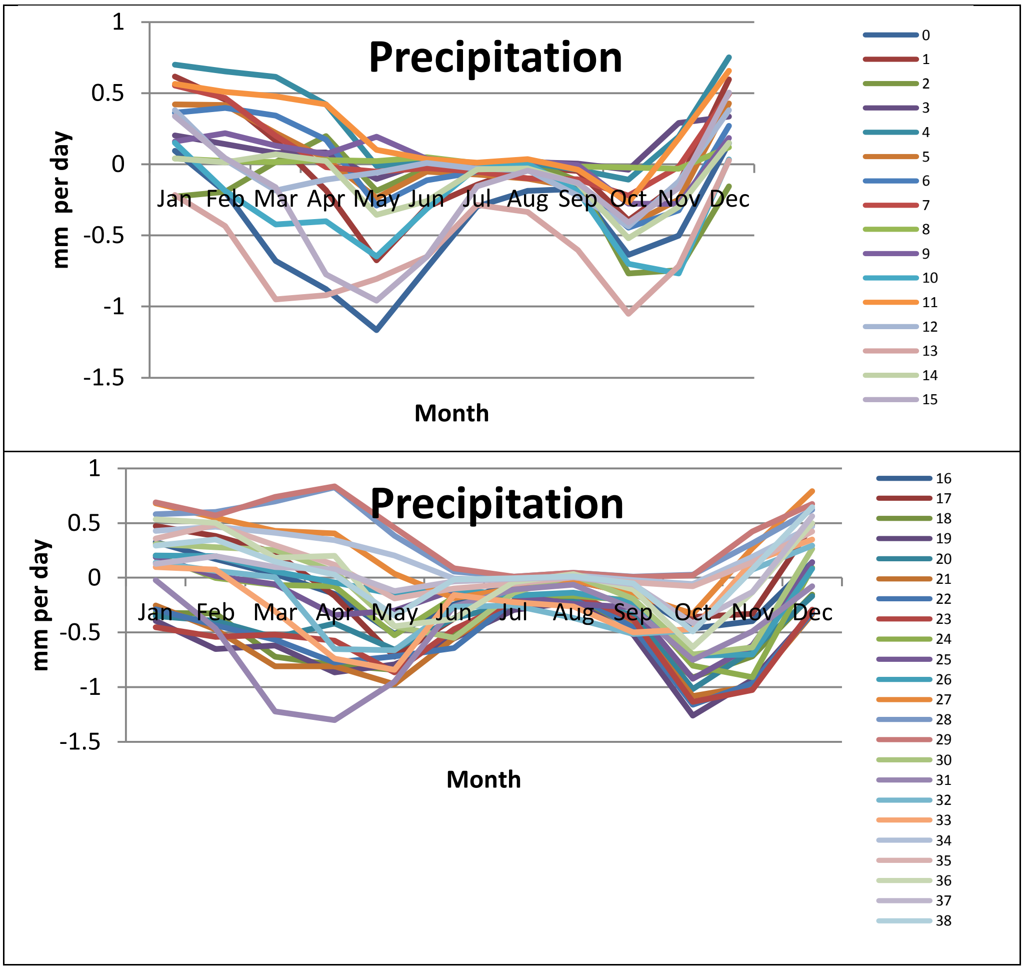


Figure 6.4: Precipitation anomaly (bias) for the 38 models under RCP8.5 scenario

6.2.3.2 Hydrological model

Calculation of streamflow is necessary to measure SRI. Therefore, it is necessary to run a hydrological model (WEAP model) to examine the streamflow. The module of hydrology in WEAP is spatially extended, with a study area constructed as a set of sub-basins which create the whole of the Zayandeh Rud basin. The spatial continuity of the WEAP application across a catchment provides all terrestrial factors for simulation of the hydrologic cycle. The calibrated WEAP model was selected as the WEAP platform with its integrated hydrology module can run the model under the ensemble of future climate scenarios easily. Moreover, the WEAP model can simulate different assumption scenarios which are essential to determine the impact of climate change on meteorological, hydrological and socio-economic drought.

The climate forcing monthly data set of precipitation, temperature, relative humidity and wind speed are used for sub-catchments which are fractionally separated into land use/land cover classes. The baseline year range for the climate model is 1971-2005 and the future period is 2006-2100.

A water balance model for each land use/land cover class divides water into surface runoff, infiltration, evapotranspiration, interflow, and percolation and base flow factors. Each fractional areas' values within a sub-basin altogether show the response of the lumped hydrology. In this study the Rainfall Runoff model (which runs at the monthly timescale) estimates evapotranspiration for irrigated and rain-fed crops applying crop coefficients. The remainder of rainfall which is not involved in evapotranspiration is simulated as runoff to a river, or may be proportioned through runoff to a river and flow to groundwater by catchment links.

(Groves et al., 2008) provide more details of the WEAP hydrologic module. Also (Beven, 2001) makes a more general justification for this type of simulation approach.

6.2.3.3 Water Allocation Model

Water demands for the different users in the Zayandeh Rud basin have been projected to the year 2100. Projected water demands were applied to simulate the future hydrology. The assumptions for future water demands were verified from reports of the Iranian Ministry of Energy, Ministry of Agriculture (Jahad Keshavarzi) and Esfahan Regional water authority for the study area. In addition, the assumption for the future population growth rate was collated from reports of Iran's population census data 2005.As mentioned in Chapter 5, the highest priority use for water is domestic and the second priority belongs to industry, while agricultural water use has the third priority.

6.2.3.4 Future drought indices

Both the meteorological and hydrological drought indices in the future periods are computed with the same method which is used for the historical period (baseline period) and also with respect to the baseline conditions (shown in Chapter 4). It means the cumulative probability of the precipitation and runoff is converted to the z-value of a normal distribution with zero mean and unit variance(Wang et al., 2011b). The standardized precipitation index and standardized runoff index are applied to indicate the meteorological and hydrological droughts.

The Mann-Kendall test was used to estimate the trends of drought and the impact values of climate change projections on future drought characteristics such as intensity, duration and frequency.

6.3 Results

First the projection of climate variables for all models (38 models) is represented and compared with the historical simulation. Secondly, for the selection of a model (among 38 models) to use its climate data as an input to the hydrological model (to generate runoff values), the results of an empirical statistical downscaling technique are shown. The selection of a model is based on the CDF. With the CDF method, a model with the smallest bias in the raw precipitation can be selected. The main reason for this selection is based on the assumption that GCMs with a realistic current climate will have a realistic climate change signal.

Then the runoff values which are generated by the WEAP model and affected by direct influences (climatic) and indirect influences (human water abstractions) are estimated. Finally the future projection of meteorological and hydrological drought which are defined by the SPI and SRI are analysed.

6.3.1 Climate projections and impact on drought

Figure 6.5 represents a comparison of the annual cycle of the historical GCM simulations compared with observations for temperature and precipitation data from four meterological stations in the Zayandeh Rud basin. Despite the range of historical simulations for the observed annual cycle being wide, the ensemble mean catches the observed seasonal cycle and value of the temperature and rainfall. This gives more confidence that on average the climate projections' models simulate the climate in Zayandeh Rud on this time scale. The ensemble mean is represented in order to capture the spread in outcomes produced by the all ensembles (Buontempo, 2015).

The figure explains both temperature and precipitation values of each ensemble member. Furthermore, the monthly precipitation simulation produced by the mean of ensembles shows a smaller bias with observed data.

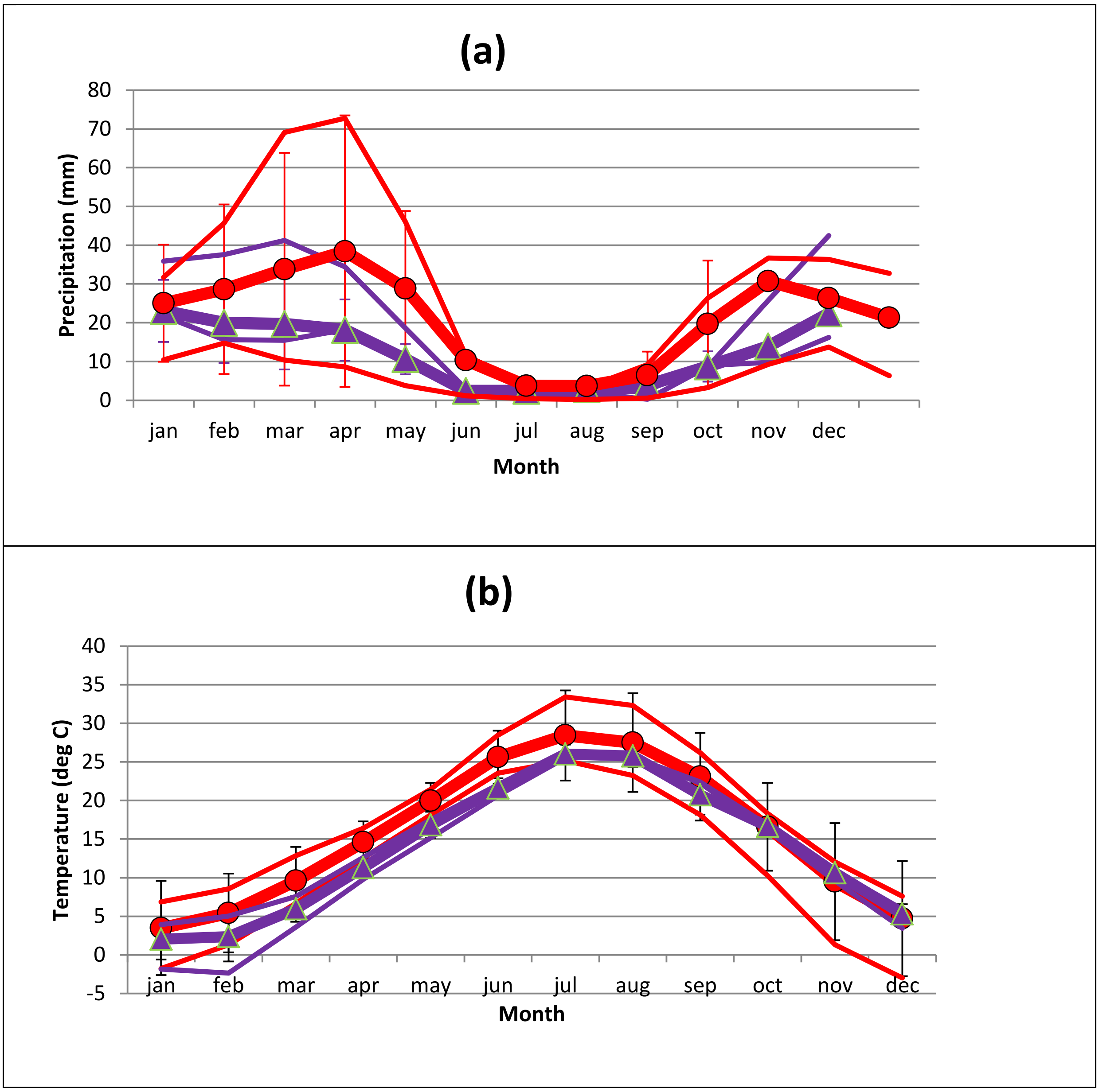


Figure 6.5: Yearly fluctuations of monthly mean rainfall (a)and temperature (b) from 1971 to 2005 is shown. The data has been averaged for the four meteorological stations and compared with the ensemble of historical GCM simulations for the same 34-yr period. The thick and thin purple lines show the mean and range of observed monthly values respectively. The thick and thin red lines indicate the mean and range of the ensemble means from 38 GCMs respectively. The vertical lines show ± standard deviation from the means for the observations and GCMs projections.

Figure 6.6 indicates the RCP8.5 simulations for 2006-2100. In the future (2006-2100) temperature increases on average of about 4 ^{O}C are usually statistically significant ($p<0.01$) compared to 1971-2005 in 8 out of 12 months. Also generally precipitation is projected to decrease in the future. The statistically significant ($p<0.01$) changes occur during the period from January to May.

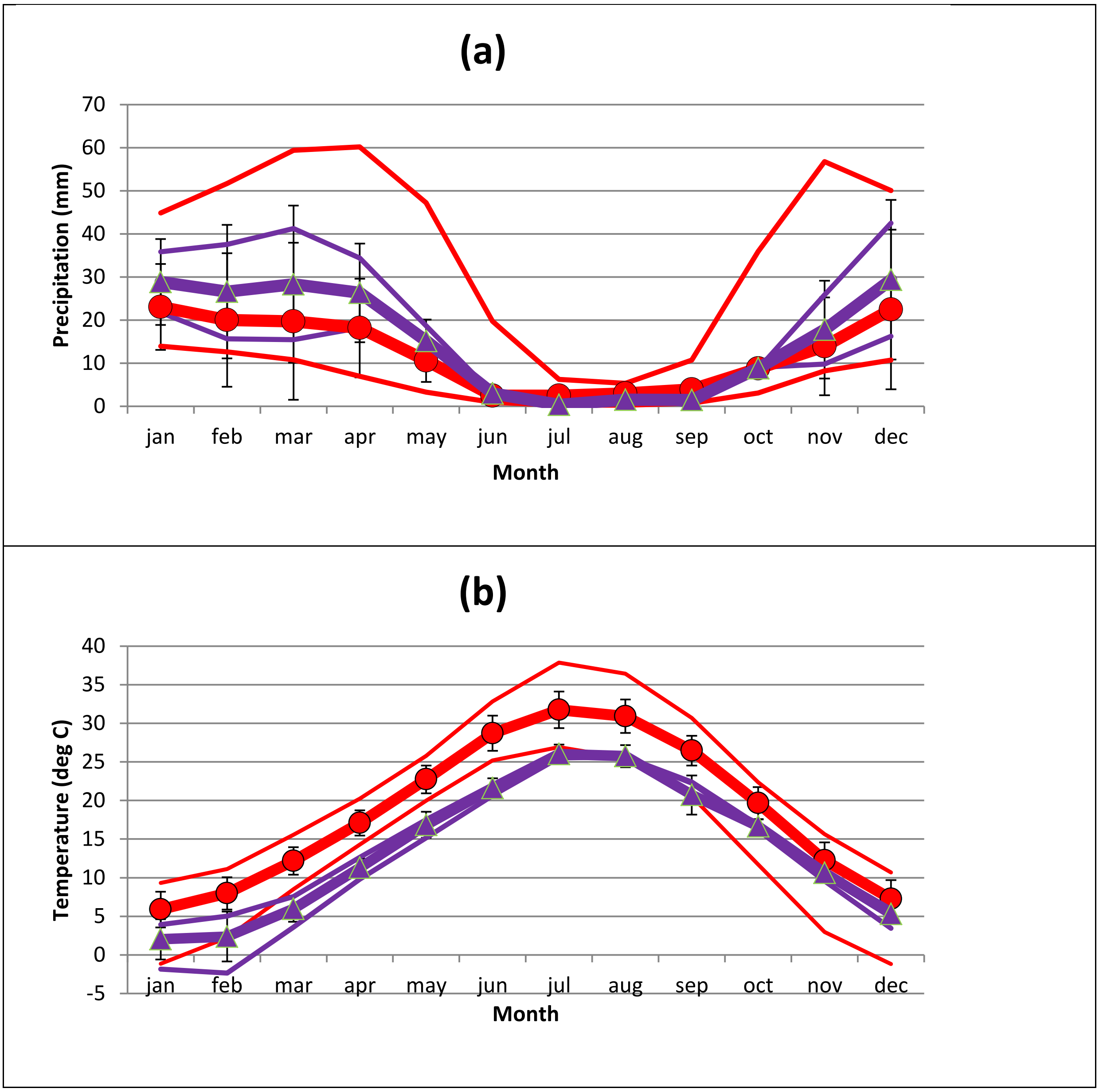


Figure 6.6: Annual cycle of monthly mean rainfall (a) and temperature (b) averaged for the four meteorological stations in Zayandeh Rud basin from 1971-2005 is shown is this figure. This has been compared with the ensemble of downscaled RCP 8.5GCM simulations done for the period 2006-2100. The thick and thin purple lines show the mean and range of observed monthly values respectively. The red and black lines are the mean and range of the ensemble means from 38 GCMs respectively. The vertical lines show standard deviation from the means for the observations and GCMs projections.

Also, the trends of upward or downward monthly precipitation for three particular models are examined. The trend analysed by the Mann-Kendall test and Kendall's Tau values are shown in Table 6.1. In the table the upward trends are shown in orange and the downward trends are shown in blue.

Table 6.1: Upward and downward trends (bold or bold italic) of monthly precipitation of observed data and the three models which have the best results of precipitation anomaly (2006-2100). The number shows the Kendall's Tau values with p<0.05.

Obs or Model	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Observed	0.20	0.41	0.21	0.13	0.44	0.36	**0.04***	**0.04***	**0.03***	0.14	0.19	0.47	0.38
HadCM3	0.20	0.40	0.39	0.27	0.43	0.17	**0.03***	**0.02***	**0.05***	0.36	0.39	0.42	0.32
CCSM4	0.18	0.22	0.14	0.34	0.22	**0.03***	**0.05***	**0.02***	0.2	0.36	***0.04***	0.17	0.32
MRI-CGCM3	0.18	0.19	0.21	0.49	0.38	0.05	0.09	0.03	0.4	***0.05***	***0.04***	0.22	0.40

6.3.2 Selection climate model to input to the hydrological model

In order to use the variables from the GCM model as an input for the hydrologic model (WEAP), the best model needs to be selected. Although the downscaling method removes the GCM bias in the mean and the variance, selecting the best model with CDF is desirable, because it is assumed that a model with a realistic current climate has a more realistic climate change signal. Comparison between observed and simulated climate change to select the best model is not easy; as climate for both observed and simulated conditions varies as a result of increasing atmospheric greenhouse gas concentration or other forcing changes (forced signal) plus natural variability (natural variability noise) under these conditions. The cumulative distribution function for mean monthly precipitation was used to select the best model. CDF is an empirical statistical technique which shows how GCM simulated values match with observed values at the same period of time (1971-2005) (Subimal and Pradeep, 2008, Maurer and Pierce, 2014). Internal variability simulated and observed time series do not match in time, however for the CDF this does not matter, as it describes only the distribution regardless of when the individual values were observed or simulated. As shown in Figure 6.7, GCM outputs have deviations from the observed data for 1971-2005. Significant differences between the CDFs are derived with different GCM models; however only one model has a CDF similar to the observed data as shown in Figure 6.8.

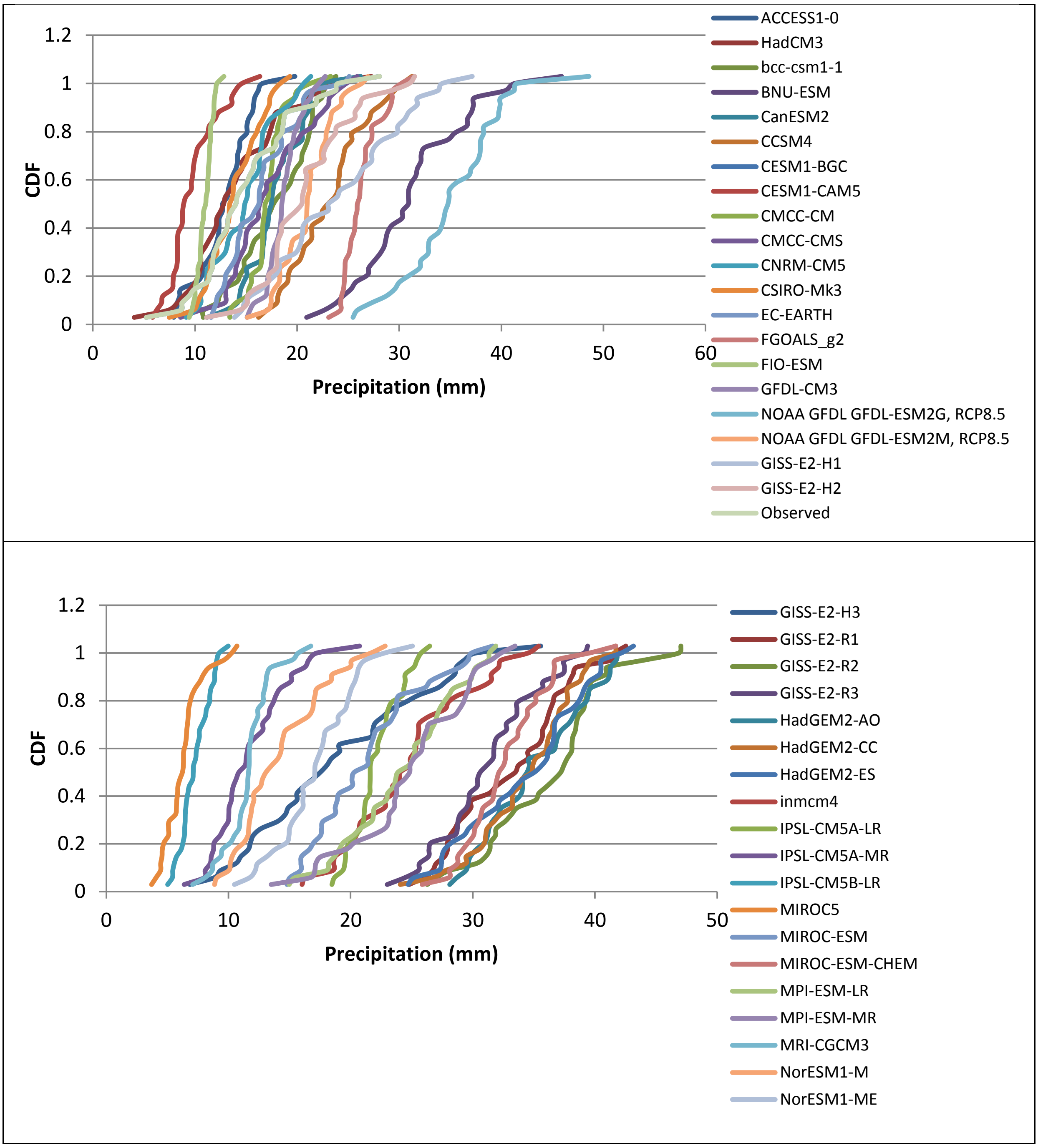


Figure 6.7: Cumulative distribution function of the 38 models for mean monthly precipitation

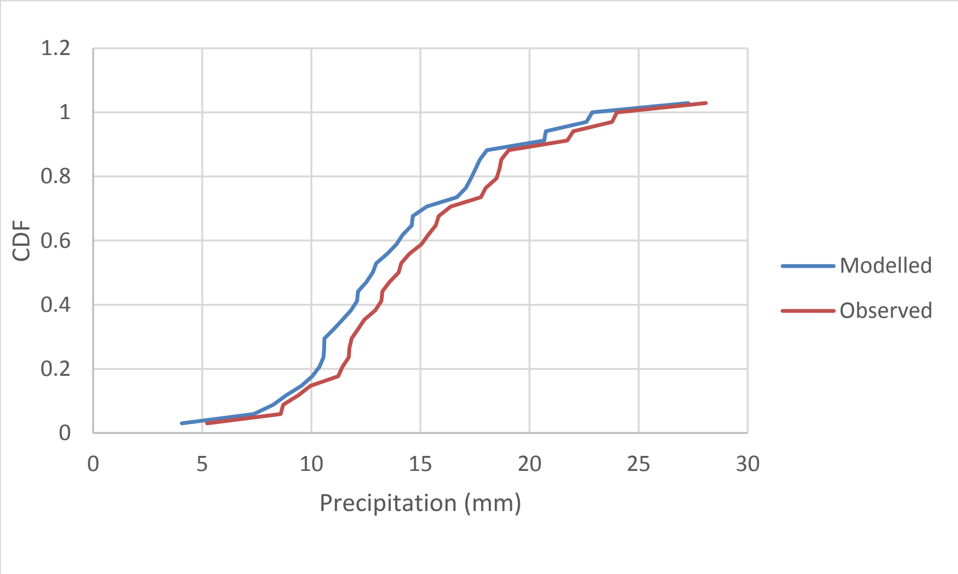


Figure 6.8: Cumulative distribution function of the best model for mean monthly precipitation

6.3.3 River flow simulation and impact of human water abstraction on reduction of flow

Water demands for the different users in the Zayandeh Rud basin have been projected to the year 2100. Projected water demands have been applied to simulate the future flow and future hydrology.

For the projection of water requirements of irrigated agriculture, the sum of the crop water needs were estimated from the future climate time series using WEAP's internal evapotranspiration routine and its delegation of losses incurred in delivering water to meet evaporative requirement. These projections are based on the assumption that both irrigation water management efficiency and cropping patterns continue unchanged as the climate changes in the future.

However the historical evidence (Molle et al., 2009, Molle et al., 2004) and analysis of the data from the Iran Census Center indicates that there will be a 1.5% growth in domestic water demand over the next few years. This would be as a result of continuous population growth and the improvement of the standard of life which will result in an increased per capita consumption. It was also determined that there will be some growth (about 2%) in the water demand from industry due to the construction of new factories in the region.

The following sections indicate the results of future agricultural, industrial, domestic and all other water demands which are used in the water allocation model of WEAP.

Irrigation demand

The total water requirement for crops has been calculated. Using the evapotranspiration (ET) and effective rainfall values in each agricultural unit, a climatic water balance has been calculated.

The formula to calculate the gallons of irrigation water needed per day(FAO, 2012a, Shaw and Pittenger, 2009, Stryker, 2011) is in Equation 5 in appendix. Figure 6.9 shows the average monthly values of future evapotranspiration in comparison with the historical values in the Zayandeh Rud basin. Also Figure 6.10 represents the projection of future irrigation demand.

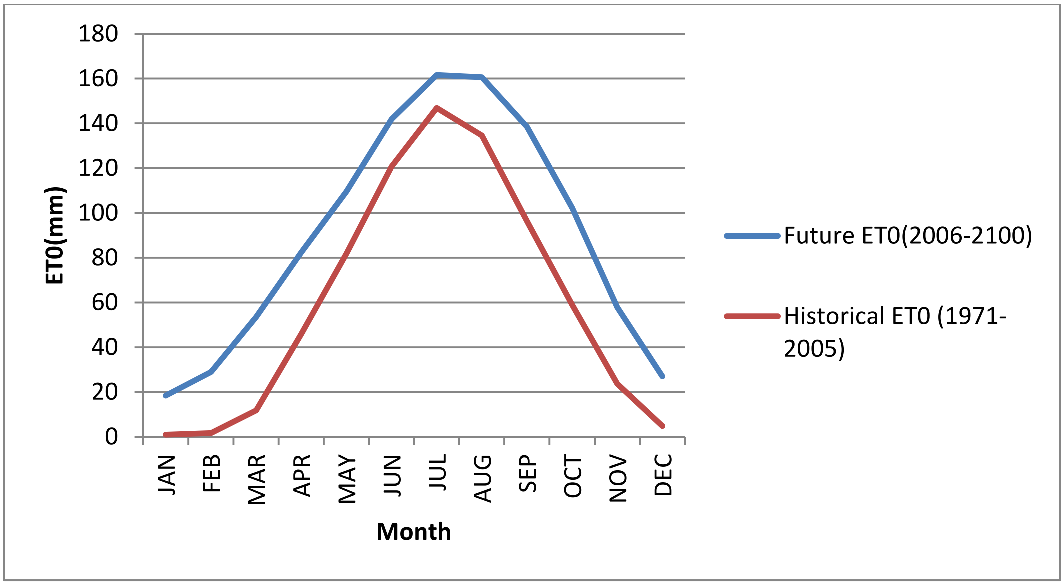


Figure 6.9: Monthly future projected evapotranspiration and the historical evapotranspiration for the Zayandeh rud river basin

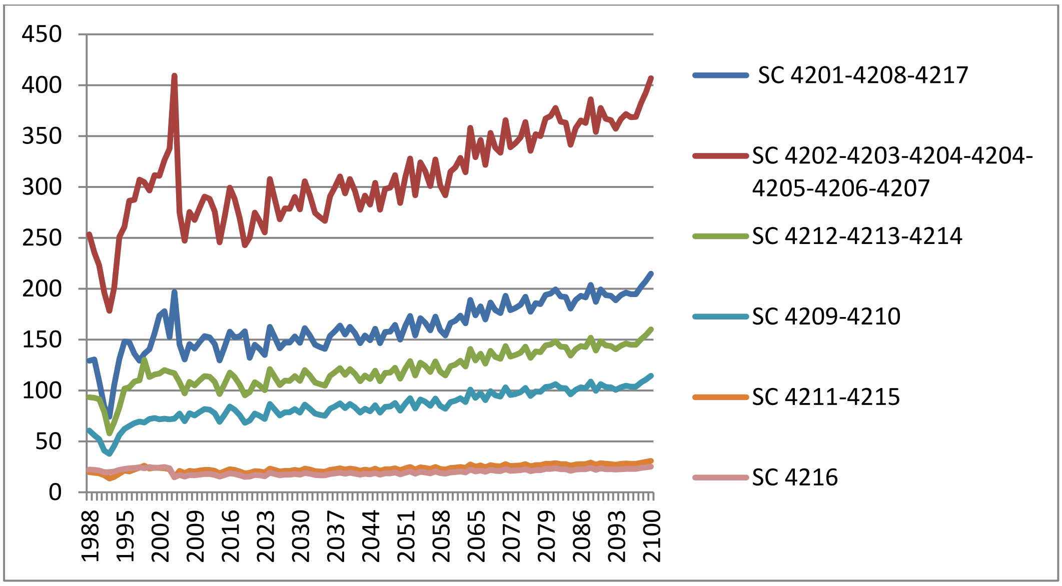


Figure 6.10: Future projected irrigation water demands for the irrigation areas (in each sub-catchment) of the Zayandeh rud river basin

Domestic water demand

It is assumed that population will increase 2.5% per year and simultaneously, also domestic water consumption will rise about 2% per year. Domestic demand is projected to grow from 238 MCM in 2000 to 626MCM in 2100 indicating a 163% increase. Figure 6.11 represents the projected population and domestic demand. The monthly variation utilization pattern was assumed to stay the same to the end of the simulation period; as the sewage system is weak and water loss is high, so return flow is too low and negligible for domestic consumptions.

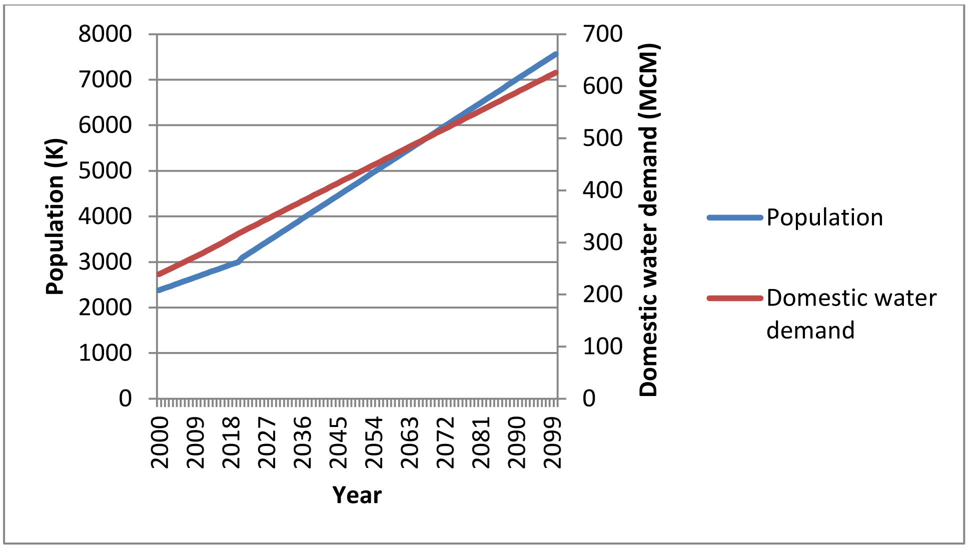


Figure 6.11: Future projected population and domestic water demands for the Zayandeh rud river basin

Industrial demand

Two main industrial users of water e.g. steelworks, iron smelter are extending and developing their works; so it is expected their water consumption will increase 4% per year after 2016. Projected industrial water demands are indicated in Figure 6.12.

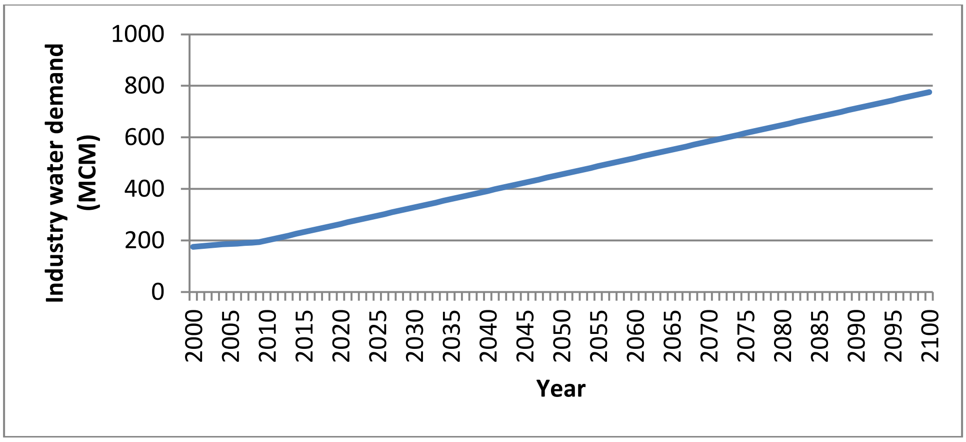


Figure 6.12: future projected industrial water demands for the Zayandeh rud river basin

Inter-basin transfers

Water supplies delivered to Yazd and to Kashan remain constant for the future: 80MCM can be delivered to Yazd, Kashan will receive 45 MCM per year. Also, from 2010, additional surface water started to transfer (16MCM) to the city of Natanz-Ardestan (which neighbours of the basin).

Ecological reserve (environmental demand)

The Environment Organization of Esfahan determines a minimum flow (70 MCM per year) into Gavkhouni Swamp; for future projection of the environmental demand, the minimum remains constant.

To obtain the total impact of human water use on the drought, the flow upstream and downstream of the Zayandeh Rud basin has been compared with total water consumption (for agriculture, domestic and industry) (Figure 6.13). With respect to the assumption for increasing population and measuring irrigation demands, generally the water demands expect to increase about 4% per year (2006-2100). It should be noted that because of a lack of groundwater, the water users mostly depend on surface water. The figure shows that the flow downstream is too low and the flow upstream is higher; however upstream the river flow is not able to cover all water demands during 2006 to 2100.

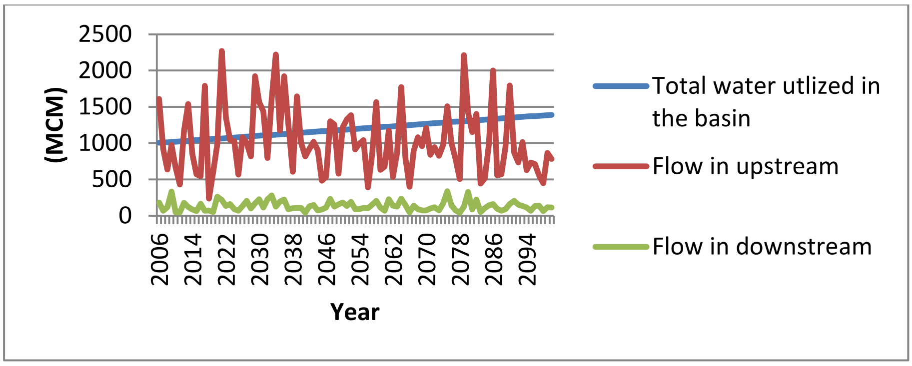


Figure 6.13: Comparison of average water supply and demand in the Zayandeh rud basin over the period 2006-2100

The Zayandeh Rud river flow with and without human abstraction has been compared in Figure 6.14. Annual river flow and peak flow declined due to increased evapotranspiration as a result of irrigation water use when compared with the flow without human abstraction. Human water abstraction exceeds the effects of low flow during the given drought period.

In the Zayandeh Rud basin the reservoir regulating measures are not sufficient to compensate for the abstraction and therefore the low flow regime changes to even drier conditions. The following sections show the drought severity and vulnerability which includes both climate change and human abstractions' impacts. Also the figure shows that for some years (such as 2083, 2084, 2087 and 2088) because of consecutive dry years with low precipitation and high evapotranspiration, the flow reduction is significant. The statistical analysis to compare amount of flow with and without human abstraction shows in Table 6.2 in appendix .

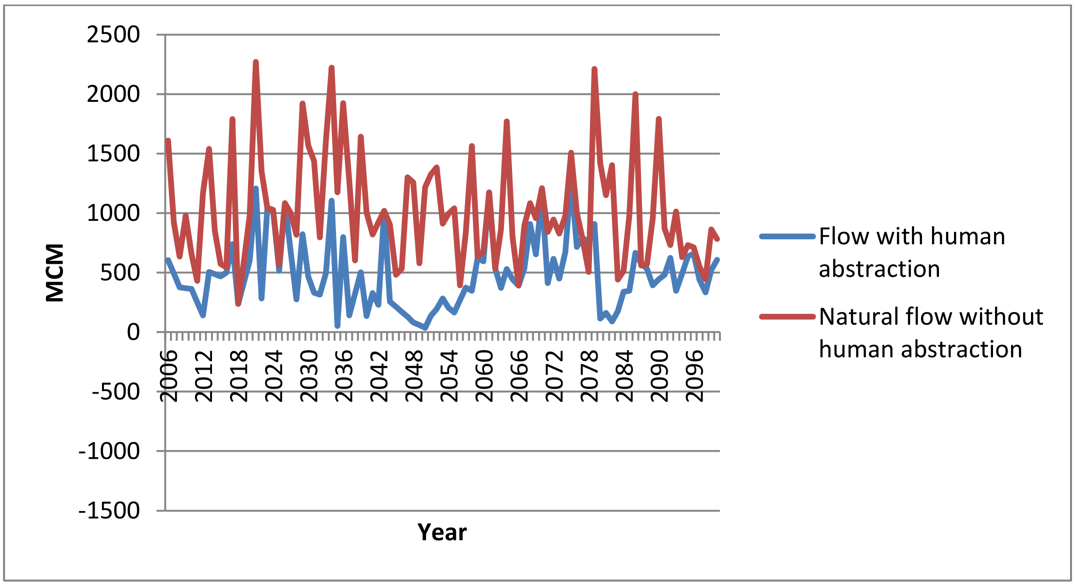


Figure 6.14: Comparison measured flow and flow with demand abstraction over the period of 2006-2100

Simulated stream flows under climate change and human abstractions are shown for the four stations and overall basin respectively in Figure 6.15. Stream flows for all sub-basins show a decreasing trend. The Mann-Kendall test was applied on the simulated stream flow which confirmed the presence of a decreasing trend in Figures 6.15 and 6.16. At a 5% significant level (α), the null hypothesis stating there is no trend in the simulated stream flow was rejected. Table 6.2 indicates the results of the trend analysis.

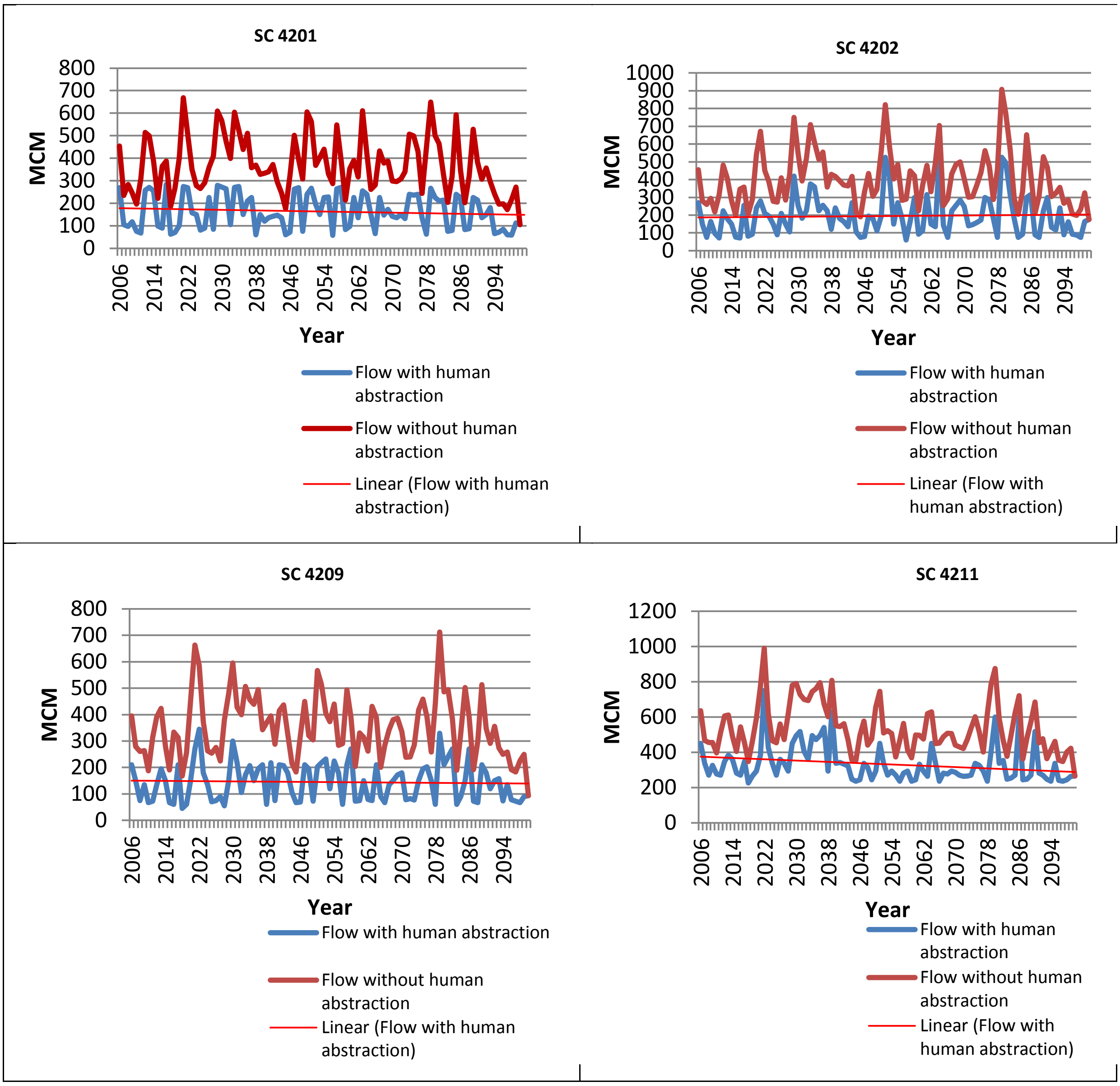


Figure 6.15: Future simulated stream flows for the four stations in Zayandeh rud river basin

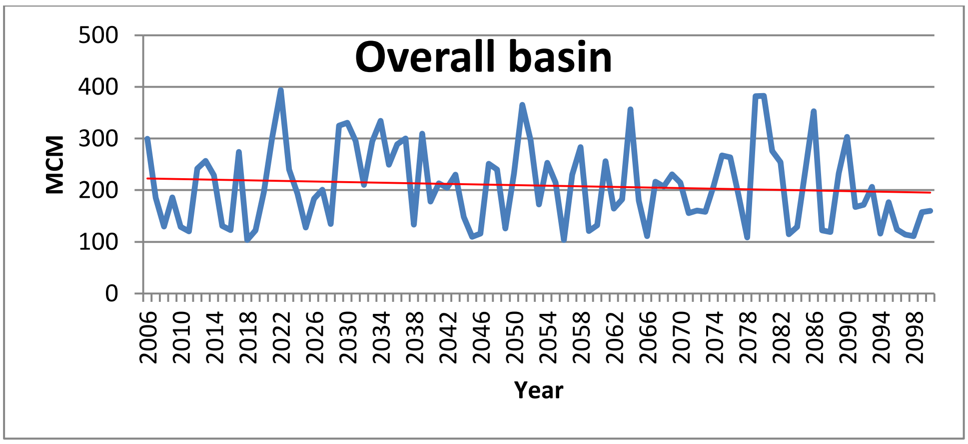


Figure 6.16: Future simulated stream flows for whole the Zayandeh rud river basin

Table 6.2: The trend result of Stream flow for the period year of 2006-2100

Area	P-Value of Trend test	Kendall's Tau
Sub-basin 4201	<0.05	-0.34
Sub-basin 4202	<0.05	-0.03
Sub-basin 4209	<0.05	-0.25
Sub-basin 4211	<0.05	-0.36
Overall basin	<0.05	-0.33

A mean monthly stream flow analysis was carried out on the 34 year historical stream flow recorded at the 4 gauges applied to calculate overall basin performance in comparison with the simulated stream flow statistics (Figure 6.17).

The figure shows the historical mean monthly stream flows are higher than the simulated values in the future. This can be attributed to the fact that rainfall is predicted to be less in the future.

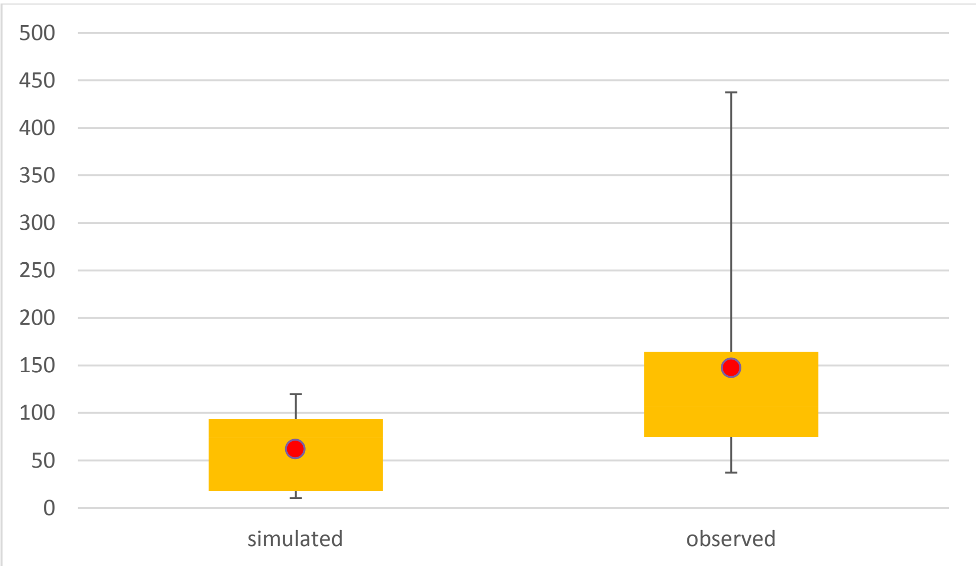


Figure 6.17: The box plots of monthly stream flow for observed data (1971-2005) and for future simulation data (2006-2100). In each box, the central points is the mean value the lower and upper edges of the box are the 25th and 75th percentiles, respectively, and the whiskers extend to the min and max data points.

6.3.4 Projected change of intensity-duration and frequency of drought

Precipitation data from the climate model was used to project future meteorological drought. Also for determining hydrological drought, the WEAP model was applied to project future runoff given the precipitation, temperature, relative humidity and wind speed. For drought projections, ensemble mean monthly precipitation should not be applied since the averaging process decreases the monthly variation of precipitation and may give misleading outputs(Liu et al., 2012). One of the 38 models was chosen because it matched the 1970-2005 observational periods with the most similarities from a statistical point of view (by using Student's test for significance between the observed climatic variables and the historical simulation models). Figure 6.18 shows the time series for two indices (SPI, SRI) for near (2006-2040) and far (2041-2075) future periods. Figure 6.19 shows that the Zayandeh Rud basin will experience 10 major droughts (in 2008, 2010, 2011, 2015, 2016, 2018, 2019, 2025, 2028 and 2038) in the near future and 8 major droughts (in 2045, 2046, 2049, 2056, 2059, 2060, 2066, 2075) in the far future. The severe droughts on the SPI are projected to be more severe than those on the SRI. However SRI is similar to SPI in terms of onset and timing of droughts. Also, comparing the time series for the SPI and SRI shows that the variability of SPI is more significant with weaker persistence compared to SRI; because the rainfall variability was filtered by the hydrologic system of vegetation, topography and soil.

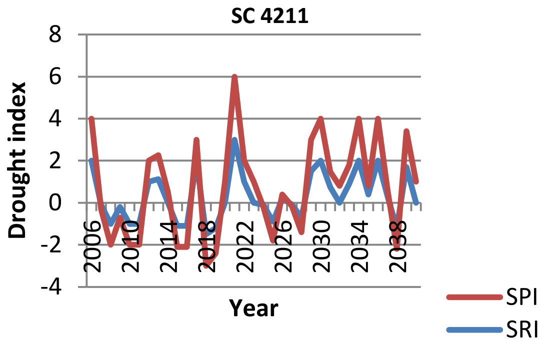
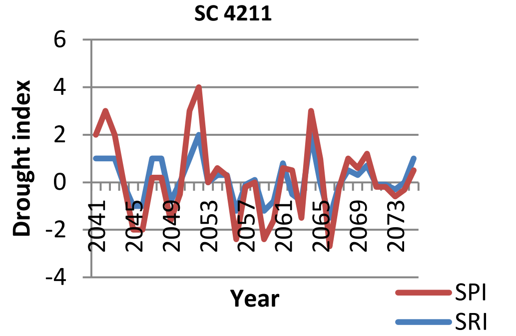
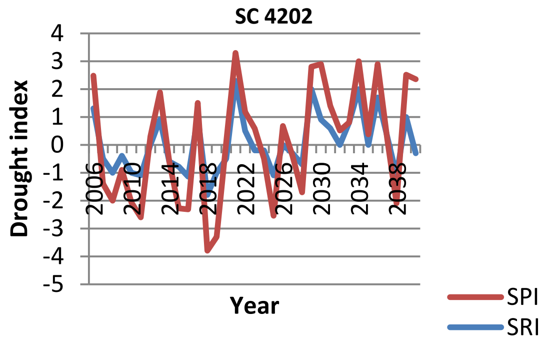
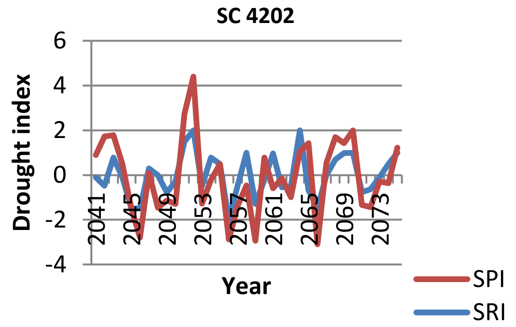
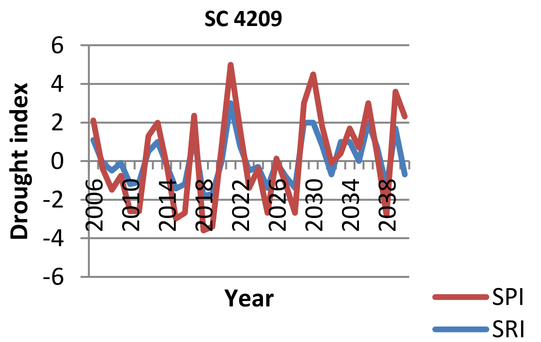
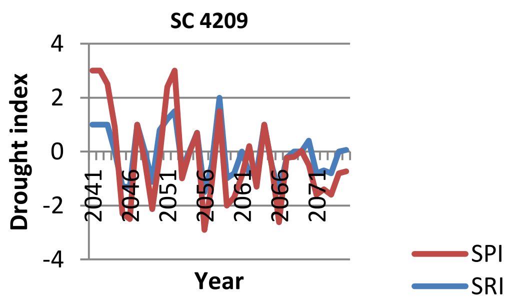
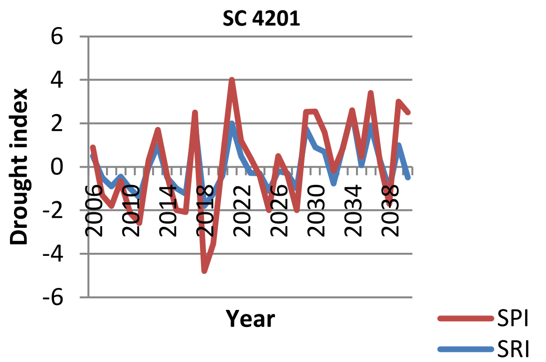
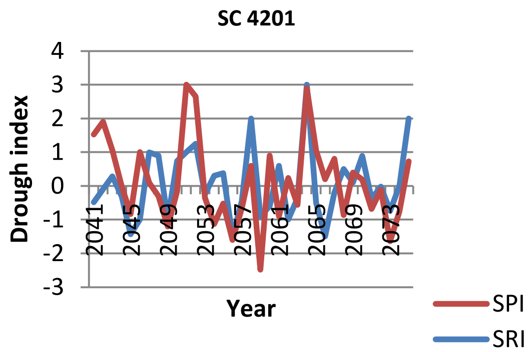
Near future (2006-2040)	Far future(2041-2075)
	
	
	
	

Figure 6.18: Projected time series variation of SPI and SRI for four stations of Zayandeh rud basin for the near future (2005-2040) in left and for far future (2041-2075) in right

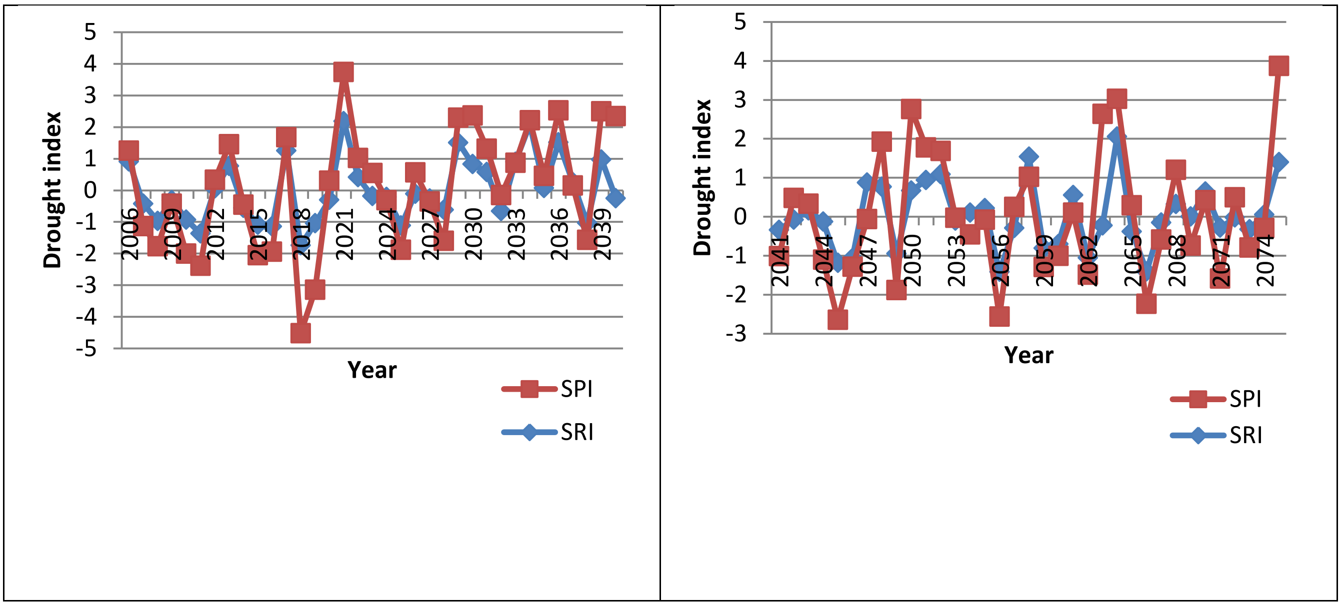


Figure 6.19: Projected time series variation of SPI and SRI for the near future (2005-2040) in left and for far future (2041-2100) in right for the Zayandeh rud basin.

The most significant dry years are extracted from Figures 6.18 and 6.19, then the minimum index, driest month and maximum duration for both meteorological and hydrological are analysed and are shown in Tables 6.3 and 6.4. The red in the tables shows the longest duration (10 to 12 months) and the blue colour illustrates the shortest duration (1 to 3 months). Also, the tables indicate the intensity of the most significant meteorological droughts is more variable compared to hydrological drought. Table 6.3 shows that the driest month in all meteorological drought events is in winter or spring in the near future. However, the driest month in all hydrological drought events is in summer or autumn. Maximum duration for both meteorological and hydrological drought events is between 5 to 12 months for the near future. The minimum index for both meteorological and hydrological drought in the year of 2018 is the most significant.

Table 6.3: Characteristics of droughts at 12 month timescale for the period of 2005-2040

Dry year	Drought index	Min index	Driest month	Maximum duration (month)
2008	SPI	-1.30	Apr	5
	SRI	-1.09	Aug	7
2010	SPI	-2	May	6
	SRI	-1.06	Aug	6
2011	SPI	-2	Feb	12
	SRI	-1.32	Aug	12
2015	SPI	-2	Mar	5
	SRI	-1.13	Oct	5
2016	SPI	-1.09	May	6
	SRI	-1.2	Oct	6
2018	SPI	-2	May	12
	SRI	-1.61	Sep	12
2019	SPI	-1.71	Jan	6
	SRI	-1.30	Dec	6
2025	SPI	-1.30	Jun	7
	SRI	-1.11	Aug	8
2028	SPI	-1.2	Mar	6
	SRI	-1	Jul	6
2038	SPI	-1.40	Jun	6
	SRI	-1.06	Dec	7

Table 6.4 represents the driest month in all meteorological drought events is in winter or spring for the far future. While the driest month in all hydrological drought events is in summer or autumn. Maximum duration for both meteorological and hydrological droughts is between 4 to 12 months. Furthermore the minimum index for both meteorological and hydrological drought in the year of 2056 is the most significant in the period of 2041-2075.

Table 6.4: Characteristics of droughts at 12 month timescale for the period of 2041-2075

Dry year	Drought index	Min index	Driest month	Maximum duration (month)
2045	SPI	-2	Mar	12
	SRI	-1.07	Nov	12
2046	SPI	-1.42	Jan	4
	SRI	-1.03	Dec	6
2049	SPI	-1.24	Mar	5
	SRI	-1.04	Dec	6
2056	SPI	-2	Feb	12
	SRI	-1.53	Jul	12
2059	SPI	-1.03	Mar	5
	SRI	-1	Dec	5
2060	SPI	-1.31	May	5
	SRI	-1.17	Jul	6
2066	SPI	-1.66	Apr	5
	SRI	-1.42	Dec	6
2075	SPI	-2	Jan	6
	SRI	-1.18	Dec	6

Comparison between characteristics of droughts between baseline (Table 6.5) and future time (Table 6.3 and 6.4) shows that minimum index for both meteorological and hydrological drought for near and far future time is greater than those in the baseline. Also maximum duration for meteorological drought was between 3 and 7months for 1971-2005 (Table 6.5) which is shorter than in future time. However, the maximum duration for hydrological drought was between 4 and 12 months.

Table 6.5: Characteristics of droughts at 12 month timescale for the period of 1971-2005

Dry year	Drought index	Min index	Driest month	Maximum duration (month)
1972	SPI	-1.46	Jan	3
	SRI	-0.96	Jul	4
1976	SPI	-1.44	Apr	4
	SRI	-1.14	Jul	4
1980	SPI	-1.29	Jan	3
	SRI	-0.65	Aug	4
1984	SPI	-1.40	Jan	3
	SRI	-0.98	Aug	5
1990	SPI	-1.34	Feb	4
	SRI	-1.13	Jul	4
1996	SPI	-1.46	Feb	2
	SRI	-1.17	Sep	4
1998	SPI	-1.48	Jun	7
	SRI	-1.39	Oct	12
1999	SPI	-1.49	Jan	4
	SRI	-1.41	Oct	11
2000	SPI	-1.96	Mar	8
	SRI	-1.45	Oct	11

Analysing drought frequency (Figure 6.20) shows that in general the number of drought events declines with the rise of drought duration for both drought indices. Comparison between baseline and future projections shows that the difference of the frequency varies with drought indices. For a given drought duration, the number of drought events enhances from baseline to the future. For example for SPI with a duration of 6 months, the frequency increases from 17 under the baseline to 83 and 33 under the near and far future. Also the frequency for both droughts with the maximum duration (e.g. 12 months) is increased during the near and far future.

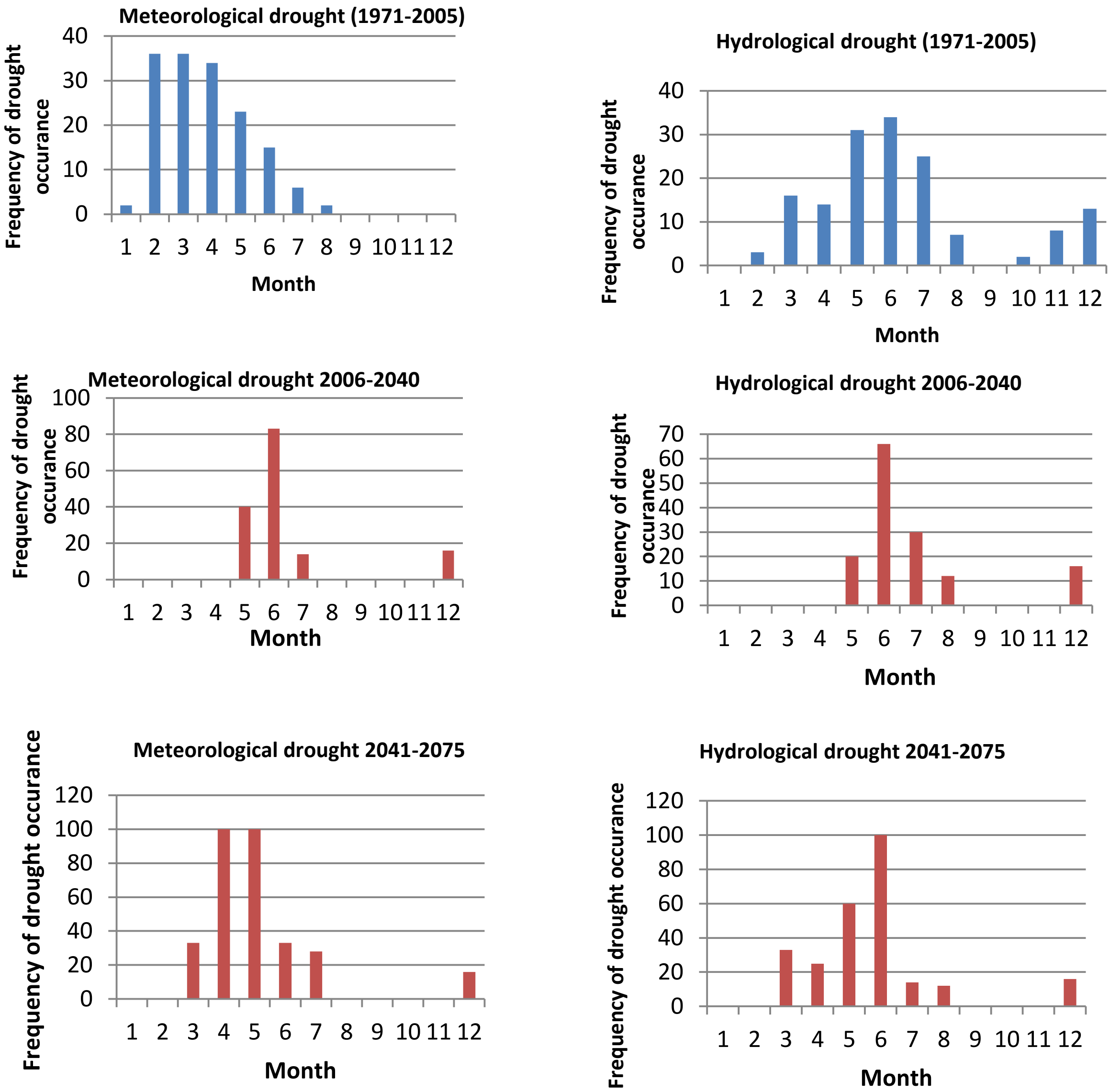


Figure 6.20: Frequency of meteorological drought occurrence in left and hydrological drought occurrence in right for baseline period (1971-2005) and near (2006-2040) and far future (2041-2075)

6.3.5 Projected change of extreme drought events

Intensity, duration and frequency of droughts are applied to analyse extreme drought events, which in practice can be more important for drought management(Wang et al., 2011b). Table 6.6 represents the longest duration for drought intensity less than -1 with the two indices. The longest duration rises from baseline to the future. For example, the longest duration for SPI grows from 40 months under baseline to 61months in the near future and 94 months in the far future. The longest duration for SRI in the near and far future is 71 and 103 months, which are 1.18 and 1.71 times more than the baseline.

Table 6.6: The longest duration (by Total Months) of drought events (Drought events here are determined by thresholds of intensity I<-1 and are estimated by SPI (standardized precipitation index), SRI (standardized runoff index)

Drought Indicator	Scenario	Total duration (Months)
SPI	Baseline	40
	RCP 8.5 (2006-2040)	61
	RCP 8.5 (2041-2075)	94
SRI	Baseline	60
	RCP 8.5 (2006-2040)	71
	RCP 8.5 (2041-2075)	103

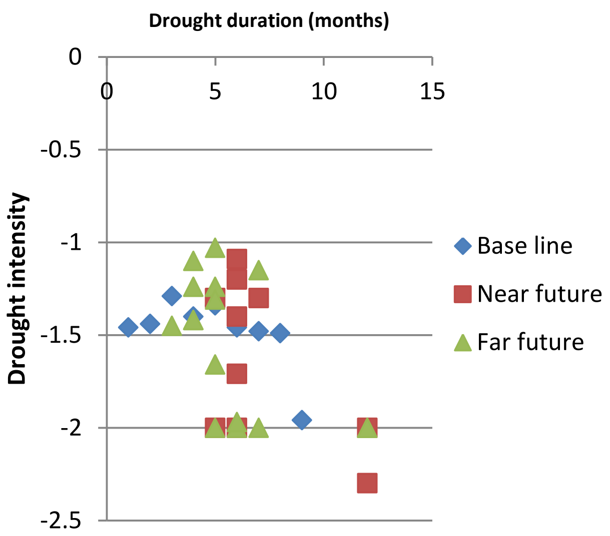
Table 6.7 indicates the change of drought intensity under baseline and future time scale. Moreover, it represents that the impact on the most severe hydrological droughts is greater than for the meteorological drought. So the intensity of the severe drought increases from -1.96 to -2 for SPI for the near future, from -1.96 to -2.1 for the far future. Also, the intensity rises from -1.46 to -1.61 for SRI for the near future and -1.45 to -1.66 for the far future.

Table 6.7: Minimum values in SPI and SRI time series

Drought Indicator(minimum value)	Baseline (1971-2005)	RCP 8.5 (2006-2040)	RCP 8.5 (2041-2075)
SPI	-1.96	-2	-2.2
SRI	-1.45	-1.61	-1.68

6.3.6 Extension of drought from meteorological to hydrological systems

The climate change impact on meteorological and hydrological drought differs under base line and future time (Wang et al., 2011b). The change in the total number of drought events and frequency of drought occurrence in terms of both drought indices under the RCP8.5 scenario is not small. Figure 6.21 indicates the number of drought events with different intensity and duration during baseline and near and far future time scales. SPI projects drought frequency to increase with durations of 5, 6 and 7 months and SRI projects drought frequency to increase with durations of 6, 8 and 12 months. While the frequency decreases for duration of 1, 2, 3 and 4 months for both SPI and SRI. Hydrological droughts are more sensitive to climate change than meteorological drought (SPI) due to the nonlinear response of soil moisture and runoff to the precipitation and temperature changes (Wang et al., 2011b). From Figure 6.1 in appendix, the precipitation change decreases from January to May and November to December significantly. Also, the significant temperature change occurs between February to June.



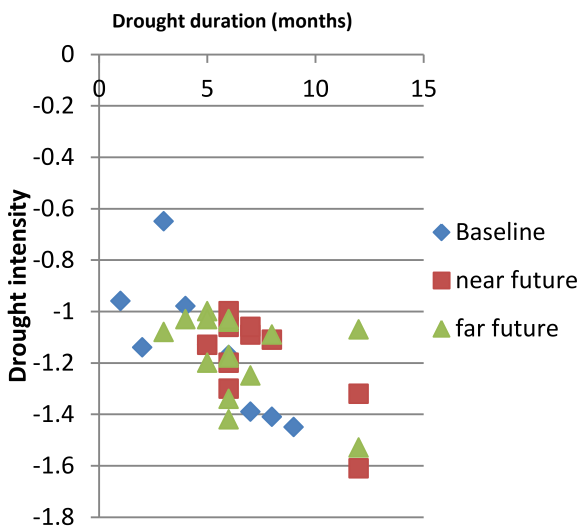


Figure 6.21: The number of meteorological droughts (in left) and hydrological droughts (in right) with intensity *I*< *-1* and the different duration

6.4 Discussion

The current GCM models hav**e** small potential resolution in their projections of future rainfall and temperature. Most of these projections are of global climate change; the regional level projection may differ within a large range (Maurer and Pierce, 2014).

With lack of regional climate models, for better water resources' planning in the developing world river basins need to combine with effects of climate change on extreme events, which are based on the downscaled GCM projections. Applying particularized downscaling methods perhaps is as data exhaustive as providing regional climate models. Therefore, the use of uncomplicated statistical methods (such as the method (section 6.2.3.1) which used in this study) is more suitable for projections in river basins of developing areas (Maraun et al., 2010). The results in this study showed that there are some differences between mean values of climate model simulations and observations (Figure 6.5 and 6.6), so, a bias correction was performed.

In this study, the potential force of future climate alteration on drought was estimated by using two drought indices (e.g. SPI and SRI). Climate alteration projections on the basis of statistical downscale through GCM climate models is applied to calculate drought frequency, severity and period by extension from meteorological to hydrological drought. At first, in order to evaluate uncertainties in the projections, a multi-model ensemble from 38 monthly GCM simulations with the severest emission scenario (RCP 8.5) from CMIP5 was applied. Previous research (Sillmann et al., 2013) mentioned that to get a better idea of changes in relation to the amount of CO_2 concentration and radiative forcing that influence climate response, developing the climate change scenarios is needed. Thus, in this study, with selecting the highest CO_2 emission scenario (e.g.RCP8.5), some uncertainty remains in the projection of future drought.

None of the SRES simulations (Dastorani, 2011) in previous studies considered projecting changes in temperature and precipitation extremes as in RCP 8.5, which has the largest radiative forcing among the scenarios. Finally, the best model (between 38 models) which matched with the observation data was selected based on CDF method. Although the presented method for selecting the best model, aims to show the strengths of the model to simulate observed climate change (specially for historical period) and assumed that the best simulation of the past can be more realistic to simulate climate change signal for future period, how ever, few limitations remain.

1) There is uncertainty in the features of the future precipitation dynamics and no single or group of ensemble model can not clearly stand out in performance of the features.
2) Selected the best model in this study based on the skill of the model in simulating past climate and so it may cause eliminate the range of possible projections for unknown type of climate change.
3) The model which selected is not a sample that capture the structural uncertainty in the model itself, for example the model did not considered uncertainty in the structure of numerical method which used.

Previous approaches only use one or some GCMs, selected randomly. Some others (for example Kettle and Andreae (2000)) use minimum, maximum or mean ensembles without analysing climatic anomalies for intra-annual variability to consider the best model for climate projection.

In this study, the impact of both possible climate change and human water use (based on assumptions) on the projected hydrological drought characteristic for 2006-2100 has been considered (Figure 6.18). Obtained future drought simulation results (in terms of intensity, duration and driest month) were compared to the historical period (Table 6.3, 6.4 and 6.5). The integration of climate models, emission scenarios and human water abstraction obtains future hydrological drought predictions.

A previous study (Wanders and Wada, 2015) which focused on global scale, only used a period of future time (e.g. 2070-2099) instead of a continuous period, to predict future hydrological drought.

Other indices such as EDI (Effective Drought Index) or PDSI (Palmer Drought Severity Index) were not used for this study; as they need daily precipitation and data of soil layers which were not available.

The negative impact of climate change on the flow regime with and without human water abstraction (Figure 6.14 and 6.15) is projected. This projection in this study is based on hydrological model of WEAP (which include some uncertainties) to determine future flow projection.

Due to the increased temperature and decreased precipitation as well as the nonlinear hydrological responses to precipitation and temperature change, they are the most important factors in the change of drought characterization. In addition, high wind speed and high evaporation increases the drought severity in the basin. The sensitivity of the indices to changes in precipitation and flow was tested. The results in this study show that both meteorological and hydrological droughts may increase in the future (Figure 6.21), primarily as a result of increased temperatures (Figure 6.6). Intensity, duration and frequency of drought are likely to rise across all time periods due to climate change and human influences (Table 6.6 and 6.7).

According to a previous study (Xiao et al., 2015), the future projected changes of temperature and precipitation in the Asian and Middle East regions may cause significant intensification of surface heat fluxes, however this effect is not directly estimated in this research. Aldo as discussed in previous research (Penalba and Rivera, 2013), decreasing precipitation and longer dry spells probably cause drought.

The rainfall in Iran is generated by Mediterranean synoptic systems, which go eastward along with western winds in the cold season. Variability in annual rainfall is made by synoptic systems and year to year change in the number of passing cyclones. Frontal Mediterranean cyclones co-operating with the western airflows make rainfall in late autumn and especially in winter in Iran. It is noteworthy that the Mediterranean system precipitation and also the possible influence of ENSO, which can increase drought risk in future in Iran, is not well simulated in future climate models (Feizi et al., 2014). However the GCMs used in this study have improved compared with previous models (Zarghami et al., 2011, Abbaspour et al., 2009). They now contain the likeness of the ocean, atmospheric chemistry, vegetation, carbon cycle, land surface, aerosol and sea ice at finer spatial resolution (Abdussalam et al., 2014).

Potential risk from drought in the future should be estimated keeping in mind the increased demands of water for domestic, industrial and agricultural uses in addition to the forecasted changes in the climatic variables, such as precipitation, temperature, humidity, wind, especially in the rapidly growing regions of Asia, the Middle East and North America (Wada et al., 2013). The anthropogenic impact on drought is less well known and such influences have seldom been surveyed.

The results in this study show that low peak flows and increased abstraction of water by humans causes more risk of hydrological drought events.

Insufficient and poor data related to land use (Diffenbaugh et al., 2015) and non-inclusion of projected population and associated demands of water have not been addressed in earlier studies. Furthermore, high uncertainities in climate change prediction models give wide ranging results. Crop pattern values in this study remain the same as historical data; but changes in population and water demands are projected. Therefore, this study is limited in terms of potential future land use changes. However, this study attempts to give some preliminary ideas of possible changes in risk of drought combining climatic changes and changes in anthropogenic demands in case of business as usual and this has not been studied for the Zayendah Rud basin of Iran.

Without awareness of possible future events, it is hard to improve the conception about future adaptation to change in the risk of drought impacts associated to climate change and water abstractions by humans. For this reason, decision makers in national and regional governments require facts regarding the potential vulnerability of drought impacts associated to climate change and how it could be decreased.

6.5 Conclusion

Projecting the potential impact of climate change on meteorological-hydrological drought is necessary, particularly for regions like Iran where the projected climate change impacts are investigated rarely for water planning and water management.

This chapter addressed the two objectives of this thesis by applying a statistical method for climate change studies to assess the potential impact of future climate change on drought characterization. An ensemble of statistically downscaled variables from GCM projections engaged in the CMIP5 was applied as analytical variables.

Changes in climate extremes by selecting the highest CO2 emission scenario (RCP8.5) may indicate larger impacts on droughts.

The analysis represents a reduction of rainfall over the basin in the future scenario. Following this change, the stream flow values will decrease and will influence the water availability for users.

Stream flows are set to reduce in the future. This has been verified from the plots and also applying the Mann-Kendall test. The magnitude of future maximum monthly stream flow is expected to decrease by 118% relative to observed maximum monthly stream flow (Figure 6.2 in appendix).

Findings from this study showed a significant potential future growth in drought cases, mainly due to warming climate and human water abstraction.

Significant meteorological drought is expected to occur in the winter and spring months of January to June. However the driest month for hydrological drought is in the summer and autumn (July to December) (e.g. no changes in seasonality of droughts compared to historic period).

It is concluded that, in the results of this work, the human influences on projected hydrological drought have been outlined; they had been missed in many projections for future hydrological drought. However this study confirms the previous study (Bierkens et al., 2012) which mentioned that human influences can account for future hydrological drought in areas of Asia, the Middle East and the Mediterranean.

Therefore, in the Zayandeh Rud basin, as an example of these regions, low flows are supposed to be even lower in future and drought will likely rise dramatically. Better scenarios of future human water demand can provide great skilful projections for the 21st century. Nevertheless, they are not available yet, as a result of the lack of comprehensive future socio-economic and land use projections that are dependent on each other.

Currently, human water abstraction has an additional influence on hydrology and water resources and so it is necessary to involve it in hydrological models which are applied for projections of future hydrological drought.

Determination of this study is based on a future modelled climate simulation that might not represent full reality. The estimation was done assuming some, but not all non-climatic factors which may influence the future dynamics of drought, will keep constant. For example: the irrigation infrastructure, cropping patterns, irrigation and farming techniques, the water distribution and water use efficiencies for the future period are speculated to be same as in the baseline (historical) period.

However, any change in the irrigation demand in future is associated to crop evapotranspiration demand forced by climate change. Evapotranspiration demand is supposed to rise as a result of temperature effects. In addition increasing future industrial and domestic water demands will affect the deficit of the river flow and hydrological drought.

CHAPTER SEVEN : LINKING FUTURE DROUGHT, WATER RESOURCES, AND DEMANDS :IMPACTS, RESPONSES AND EVALUATION OF ADAPTATION MEASURES AS SIMULATED BY A WATER MANAGEMENT MODEL

7.1 Introduction

The evaluations of climate change forces begin from the hypothesis that the future climate will be different from; an assumption that is supported by the outcomes of current global climate monitoring and the outcomes of general circulation models (GCM) applied to simulate the global climate. Through expansion, varying in future climatic conditions will make different hydrologic patterns from those in the historic stream discharge record (Van Huijgevoort et al., 2014).

Future climate change that causes changes in hydrology regimes, also probably will cause changes in water demands by differences in temperature and precipitation patterns that combine with land use change due to future population growth and development (Le Houérou, 1996). The logical consequence is that the water resource systems' models applied to analyse the forces of future climate change and to investigate adaptations should be run by applying hydrologic conditions derived from future climate scenarios and socio-economic elements (Alcamo et al., 2007).

Climate change and its influences on the water resources and water demands is a significant impact with which Iran and the rest of the world will have to manage in the 21st century (Rochdane et al., 2012).

The Zayandeh Rud river basin will have to deal with the additional challenges of climate alteration involving the adjustment of human activities reliant on water supplies, such as irrigation agriculture, to new climatic circumstances. It will need a shift in water organization and farming decisions towards more maintainable agricultural production and more efficient water allocation, dispersal and consumption.

Recent research on climate alteration has considered the evaluation of impacts, vulnerability and adjustment under biophysical or social outlooks (Downing, 2012). Most evaluations have been established on biophysical modelling, concentrating on one particular dimension of climate alteration, for instance the agronomic dimension (Moriondo et al., 2010), or the hydrological dimension (Rosegrant et al., 2000). The identification of water organization and climate alteration as multidimensional and multi-scalar, concerns (Meinke et al., 2009) verification of the requirement to combine biophysical and social features. Therefore, various kinds of integrated modelling frameworks have been improved to address several scales (from the crop to the river basin) and several dimensions of climate alteration, water and agriculture. These structures have not constantly characterized the social dimension of water consumption in adequate detail and sometimes they have underestimated the role of human reaction to climate influences.

Attempting to better characterize social problems, hydro-agronomic modelling has been widely utilized as a outstanding tool for guiding and applying water policy decisions (Blanco-Gutiérrez et al., 2013). These models can deliberate the behaviour of water users. This modelling method has been used on several scales and has been applied for the analysis of various agricultural problems (Rounsevell et al., 2003); and (George et al., 2011, Booker et al., 2012), for water allocation policies; (Qureshi et al., 2008), for groundwater overexploitation; and (Volk et al., 2008), for agriculture-driven pollution . In recent years, hydro-agronomic modelling has been used for the evaluation of influences and adjustment to climate change and the associated uncertainties (Scardigno et al., 2014). These models represent farmers' response to climate alteration influences on water supplies and agricultural production guided by economic principles. The deliberation in these models of crop growth processes and the behaviour of other water users (e.g. industrial and domestic) in the river basin has been missed.

Therefore, the objectives of this chapter:

1) To evaluate differences in past and future projected available water resources and assess vulnerability of unmet water demands during a drought period.
2) To analyse socio-economical expression and impact assessment of past and future drought scenarios (under climate change) on agricultural production.
3) To determine potential adaptation scenarios within a more conceptual and theoretical framework.

This chapter will discuss a novel application of a water evaluation and planning modelling framework used to assess climate alteration impacts in the Zayandeh Rud basin during dry years, taking into account all water users, socio-economic and hydrology systems. Analysing significant droughts and the impacts on water resources and water demands could further help water managers and decision makers to identify the risks and understand the reliability of the water system with possible adaptation scenarios (Adger et al., 2009).

The novelty of this approach lies in the capability of this integrated framework to take into consideration agronomic, economic and hydrologic processes that take place on different scales. This chapter uses water allocation modelling, including the analysis of climate change implications on all water users especially irrigation agriculture systems and the water system levels. Applying this integrated approach, this chapter evaluates the impacts of a severe climate change scenario (RCP 8.5) on the water system, on farms and crops, and examines farmers' capacity to adjust. It also investigates potential adaptation scenarios, considering the various entities relevant to water management decision-making, including the farm, irrigation system and river basin levels.

This chapter is divided into five sections:

The methodology is explained in section 2. This section describes the WEAP model of the Zayandeh Rud, which gives access to analyse future climate change and water management scenarios under future drought conditions. Scenarios are story lines of how a future system can derive over time. These can provide a wide range of “what if” questions (Purkey et al., 2008). Therefore, we can estimate the implications of several internal and external drivers of change, and how the resulting changes can be decreased by policy and/or technical interventions. WEAP can apply to calculate the water supply and demand impacts of a range of future changes in demography, land use and climate.

The outcomes of these determinations can be applied to lead the improvement of adaptation cases (section 3) that area mixture of management and/or infrastructural changes that increase the water productivity of the system.

A WEAP model was applied to determine the impact of the climate scenario (RCP 8.5) in the region under future drought scenarios and to examine how water management under some adaptations could deal with the impacts.

Sections 3 and 4 are followed by results and a discussion that documents the parameters to be used for future adaptation scenarios and uncertainty in projections of future water resources management strategy. The summary and conclusions are shown in section 5.

7.2 Materials and methodology

7.2.1 Scenario development

In this study, scenarios investigated how a water system will react to several statuses such as new policies, population change, and new technologies. The simulated results from the adaptation scenarios are compared with a reference scenario to evaluate their influences on the water system. The reference scenario is based on a future assumption without any adaptation strategies.

Four adaptation scenarios were made to determine their potential to alleviate the forces of climate change on the Zayandeh Rud basin. As climate change and population growth will raise the demand for water, and agricultural demand is the biggest consumer, most of the scenarios investigated potential preferences to decline agricultural demands. All scenarios were made and evaluated for the period of 2006-2100. The four adaptation scenarios are:

1. Scenario based on new additional water resources.
2. Scenario based on the establishment of new irrigation technology, like drip and sprinkler irrigation that can rise irrigation efficiency and reduce the amount of water use for irrigation.
3. Scenario based on a decline in all crop areas.
4. Scenario based on changing crop patterns to need less water.

There are some criteria for selection these scenarios. Because they are only adaptation scenarios which accepted by both water managers and stakeholders (e.g. farmers) in the Zayandeh Rud basin. Also it is assumed that these scenarios have less impacts on environment and water users. Furthermore, with regards to the capacity of the environment and financial feseability, it is assumed that the scenarios can be suitable selection.

Also at the end of the analysis of each adaptation scenario, a combination of the all adaption scenarios is desined to understand the value of the water availability and unmet demand with regards performing all adaptation scenarios in the basin.

7.2.2 Applied method

To get the results of future climate change impacts and examination of scenarios in the Zayandeh Rud basin (especially during drought period) climate data of the downscaled GCM and WEAP model were applied. The WEAP model can simulate a system of hydrology, different water allocation policies, dam working and analyse various scenarios for future alterations in a given river basin. For the climate change scenario, four adaptation scenarios were determined which depended on the reference scenario. The effect of climate change on water resources, water demands, and crop production for both the reference scenario and adaptation scenarios were evaluated. To determine the impact on water resources and water demands the output results of the WEAP model are used. To analyse the impact of climate change on the crop production, a simple regression analysis between maximum temperature and crop yield was used for a historical period of 1971-2005. Then the same trend was applied for the future period (2006-2100). Historical crop yield records were attained from yearly national yield reports of the Ministry of Agriculture-Esfahan, Iran (Ministry of Agriculture, 2013), which included data for the Zayandeh Rud basin.

7.3 Results

In this section, firstly the future impacts of climate change without adaptation strategies are analysed. The concept behind this scenario and strategy is to have a poor case scenario for the future change dealing with climate or alternative changes that probably restrain the available water. Next, the future impacts of the adaptation scenarios are determined.

7.3.1 Future impacts of climate change

By applying the modelling framework, the impacts of climate change on water supply, water demands, and crop yield are analysed.

In the project methodology, climate change is the main reason for future droughts that contain other parameters like population growth, increasing in domestic and water industry requirements and also food requirements.

7.3.1.1 Impact on water supply in past and future droughts

It is expected that climate change will have negative impacts on the available water resources. The basin's average rainfall will probably decline and the temperature increase. Figure 7.1 shows the projected storage volume of the biggest dam (Zayandeh Rud dam or reservoir) in the basin. The figure shows during dry years; there are significant decreases.

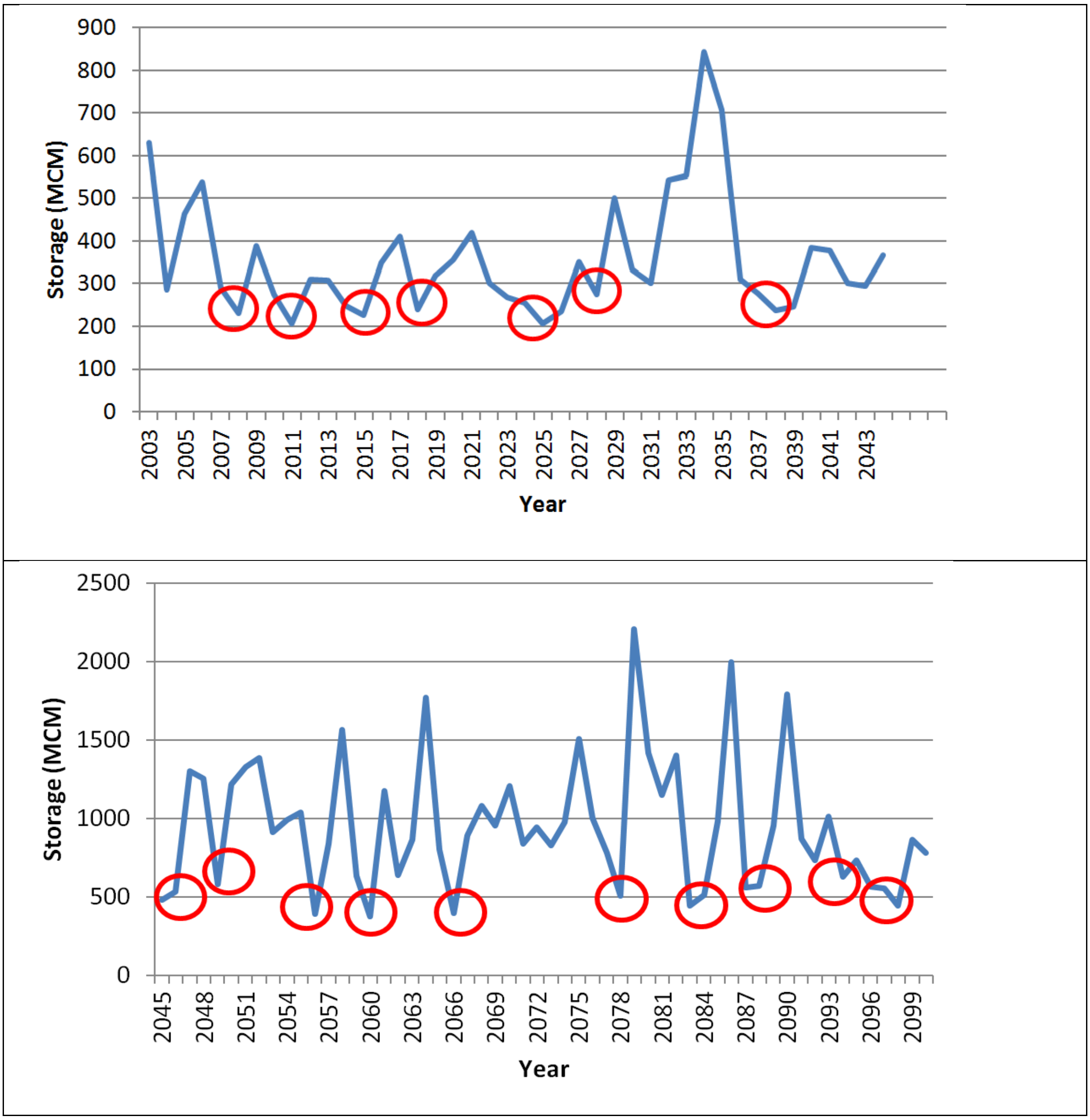


Figure 7.1: Projected storage volume of Zayandeh Rud dam for a future period, which is simulated by WEAP. The red circle shows the reduction of storage in dry years.

Also, Figure 7.2 indicates absolute values and standard deviation of monthly storage of the Zayandeh Rud dam during 2006 to 2100. The figure shows similar results to the result of the historical period during July to October the storage has the highest values. However, the dam has the lowest storage from January to March.

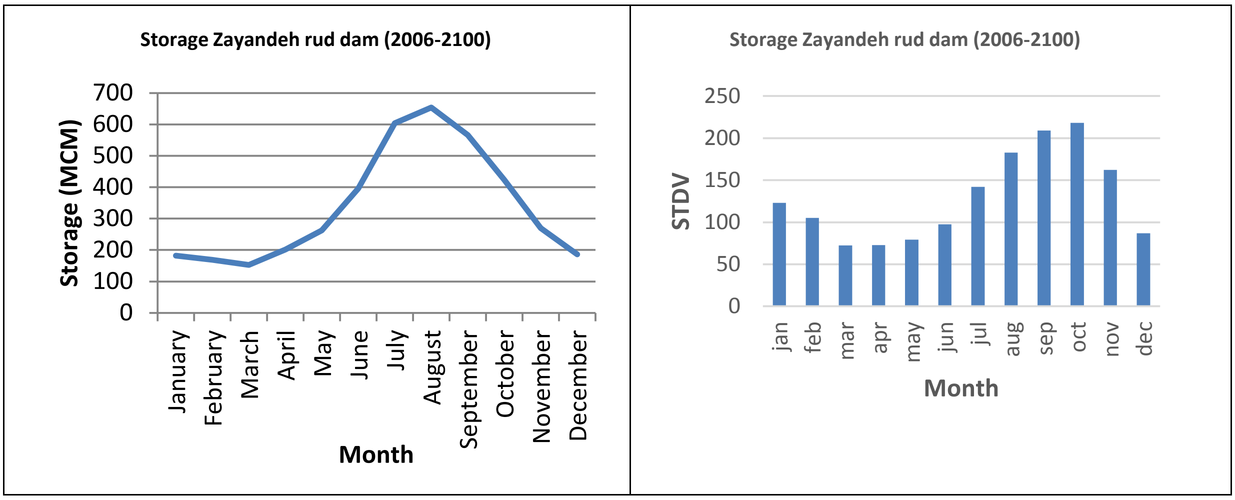


Figure 7.2: Absolute values (left) and standard deviation (right) of monthly storage of Zayandeh Rud dam during 2006-2100, which is simulated by WEAP

It is assumed that because of the deficit of stream flow and high irrigation demand, the future storage of the Chadegan dam decreases significantly between August and December especially during drought conditions (Figure 7.3). The average monthly reduction for a future drought scenario is about 55.89 MCM, more than the historical drought scenario.

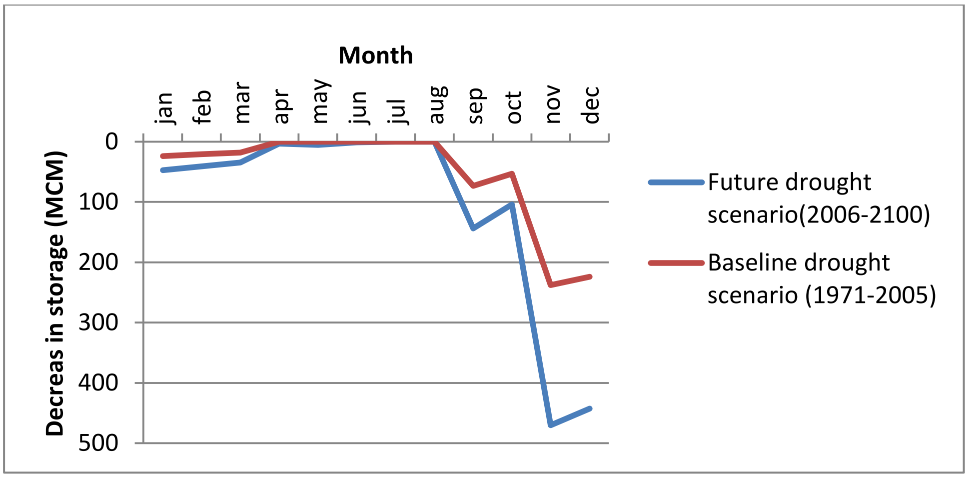


Figure 7.3: Compare decrease in storage of the Zayandeh Rud dam in the historical and future drought scenario, which is simulated by WEAP. The reduction is influenced by climate change and water demands.

Figure 7.4 represents the monthly inflows at a head of the Zayandeh Rud river during historical and future dry years. Comparing historical head flows during dry years with head flows during future droughts; the head flow decreases 6.85CMS on average. The most significant decrease occurs between July and August.

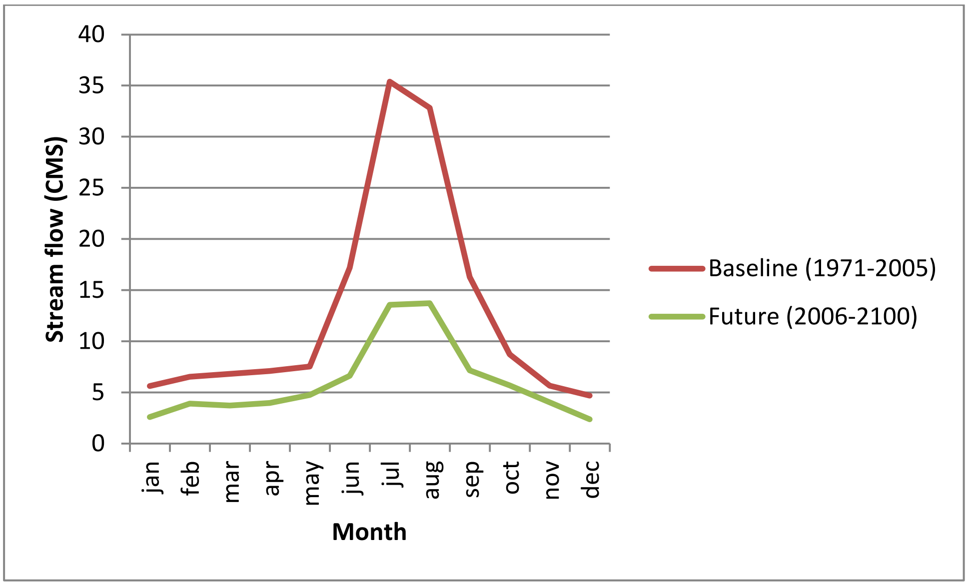


Figure 7.4: Comparison monthly head flows for the historical and future period, which is simulated by WEAP under the climate change and human water abstraction impacts.

7.3.1.2 Influence on groundwater resources

Due to the changes in precipitation and stream flows as a result of the climate change scenarios, the groundwater budget for the period of 2006-2100 was determined for the main and biggest groundwater in the Zayandeh Rud basin (located in sub-basin 4202). Figure 7.5 represents future groundwater storage that recharges by rainfall. Also, reduction of groundwater during dry years is shown.

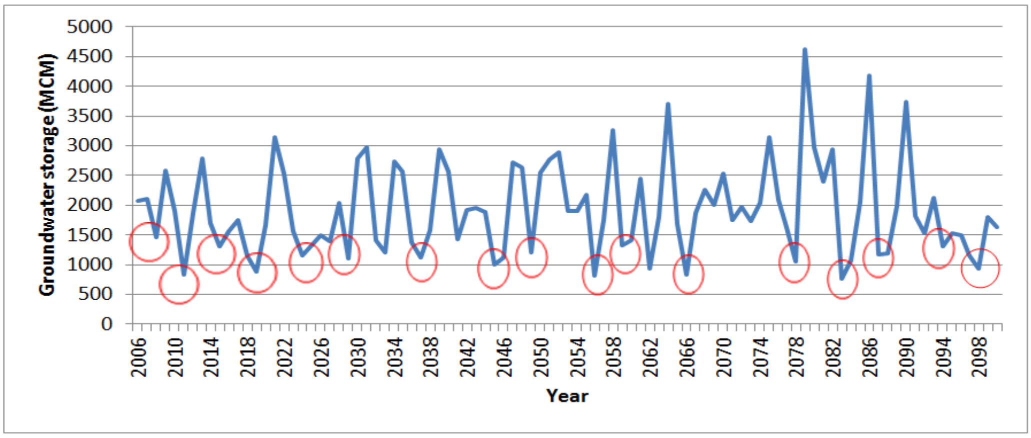


Figure 7.5: Groundwater storage for a future period (2006-2100), which is simulated by WEAP under the climate change and human water abstraction impacts. The red circle shows the reduction of storage in dry years.

Figure 7.6 indicates a negative budget which could be anticipated. In general, there is a decreasing trend (1073 MCM) for groundwater storage in the future reference scenario in comparison with the historical reference scenario. Also during a drought scenario the groundwater budget is expected to decline 1741MCM.

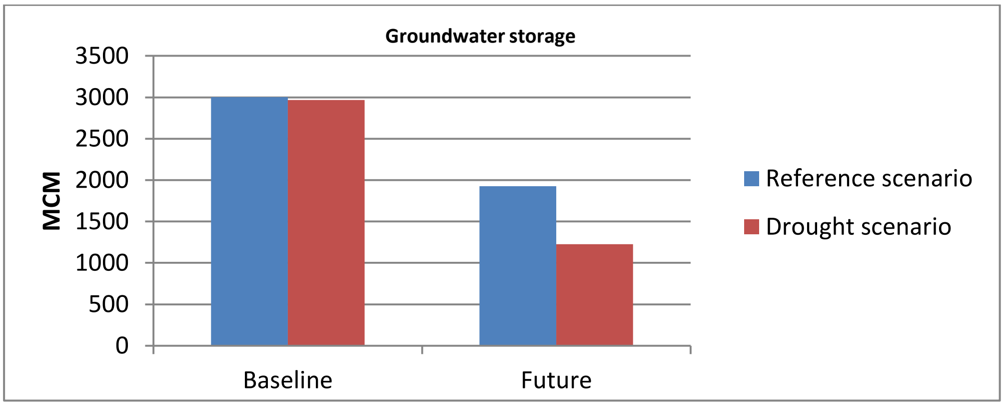


Figure 7.6: Comparison historical ground water storage (1971-2005) and future groundwater storage (2006-2100) under reference (normal condition) and drought scenarios (dry condition), which is simulated by WEAP under the climate change and human water abstraction impacts.

7.3.1.3 Impacts on water demand in past and future droughts

Future unmet water demands in each consumer water sector are estimated to analyse climate change related to future water deficits. Water deficits are determined under monthly time steps to identify the impacts of seasonal variations in stream flow. For future possible and prospective adaptation management, the first determination of water deficit in each site without adaptation scenario is necessary.

Figure 7.7 indicates the deficit appears in the months of January to April and September to December when land readiness of the crop field occurs.

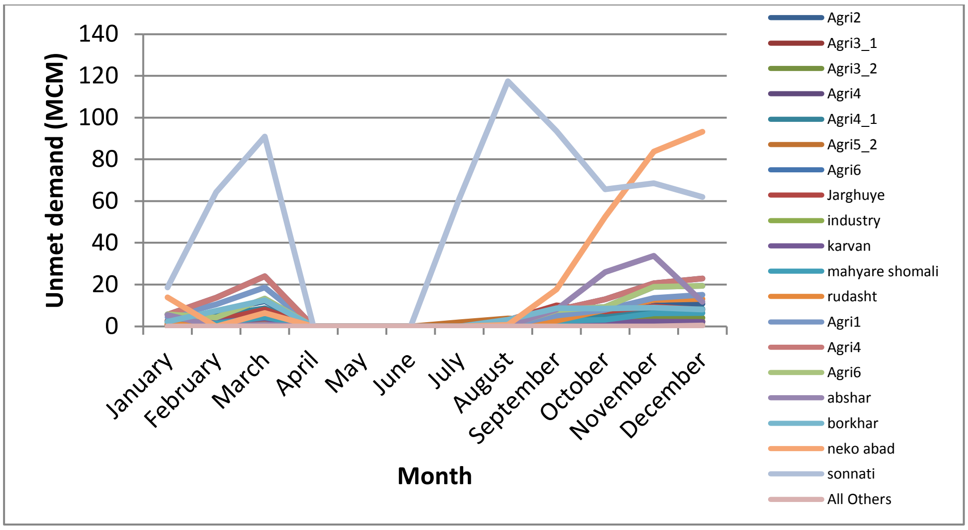


Figure 7.7: Comparison unmet demands during historical and future drought scenario which is simulated by WEAP

Figure 7.8 compares unmet water demand for each consumer water sector and each sub-basin during historical and future drought scenario.

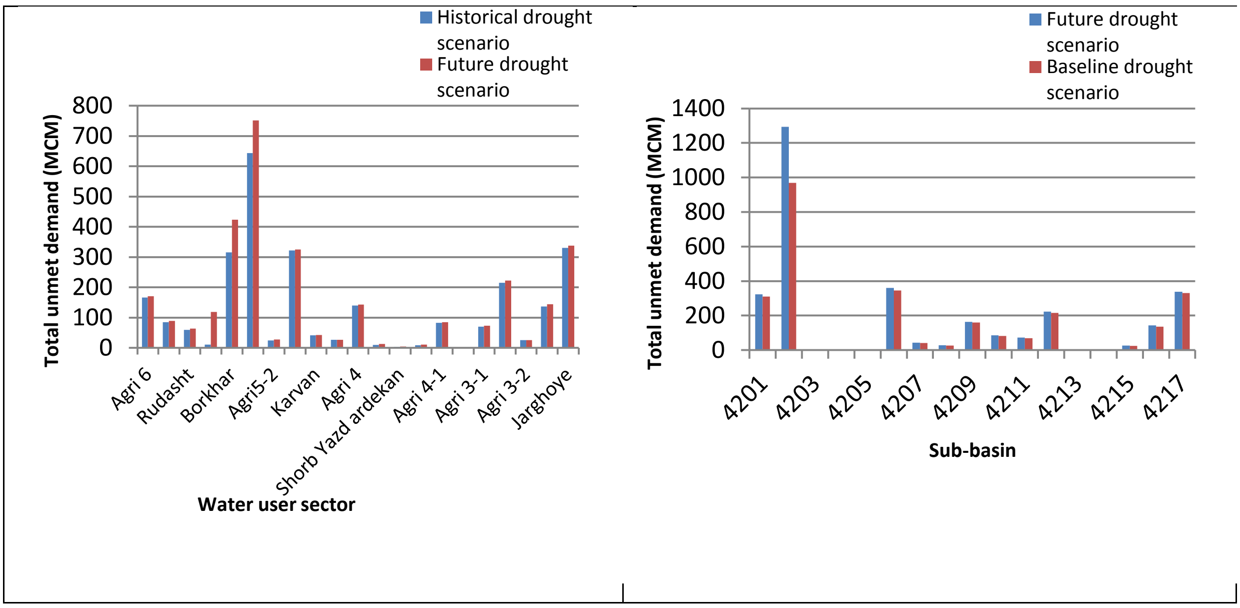


Figure 7.8: Comparison historical sum of water deficits and future sum of water deficit under reference and drought scenarios, which is simulated by WEAP

Table 7.1 indicates the unmet reliability of the demand sites during future drought scenarios. Also, a comparison of the necessary irrigation demand and the unmet demand is estimated in Table 7.1. As shown in the table, the most unmet demand belongs to water user sector of Sonnati, which is located in the sub-basin 4202. This region is one of the largest agricultural consumers in the basin as a result of high-temperature change and great evapotranspiration; the irrigation system is traditional, and irrigation efficiency is low. The area facing shortages in irrigation during the significant dry months are located in the sub-catchments 4203, 4202, 4206, 4207, 4208 and 4217. These areas are located downstream, and mainly depend on runoff values for their large irrigation demands. For domestic and industry use, the deficit is not serious as they have first and second priority to use water. The simulated deficits range from 0.02-29% of required demand. The result shows that without alternative water resources for the future, the surface water resources will not be adequate for irrigation demands.

Table 7.1: Analysis unmet demand and reliability of the demand site in each sub-basin with no adaptation. The symbol of " *" indicates the sector is agricultural. Also, the symbol of "" shows an industrial user. However, the symbol of " ***" represent the domestic user.**

Sub-basin	Water user sector (name)	Demand (MCM)	Unmet demand (MCM)	Reliability (%)	Overall reliability (%)
4201	Agri 6*	476.3854	170.7475	46.23	55.69
	Abshar*	210.6536	88.88337	60.32	
	Rudasht*	137.1965	63.81231	60.52	
4202	Industry-esf**	400	118.74	96.83	55.16
	Borkhar*	736.5873	423.3261	43.65	
	Sonnati*	782.1102	752.0291	25	
4206	Agri5-2*	28.85771	27.7478	25	39.385
	Neko-abad*	650.6105	325.3052	53.77	
4207	Karvan*	76.42956	42.46086	52.58	52.58
4208	Mahyar-shomali*	53.50388	26.75194	46.23	46.23
4209	Agri 4*	284.94	142.47	46.23	84.2275
	Industry**	432	12.38388	94.84	
	Shorb Yazd ardekan***	55	1.12	98.02	
	Shorb Sheikh***	249	10.69272	97.82	
4210	Agri 4-1*	211.6868	84.67472	46.23	71.915
	Kashan shorb***	7.9	0.25	97.6	
4211	Agri 3-1*	182.1206	72.84825	52.58	52.58
4212	Agri 2*	445.4453	222.7227	47.42	47.42
4215	Agri 3-2*	62.575	25.03	52.5	52.5
4216	Agri 1*	359.3061	143.7224	52.58	52.58
4217	Jarghoye*	540.5444	337.8403	43.65	43.65

Figure 7.9 shows in future drought scenarios the reliability decreases The sub-basins 4209 and 4210 have the highest reliability of water supplies to deliver water to the demand site. The lowest reliability belongs to the sub-basin 4206.

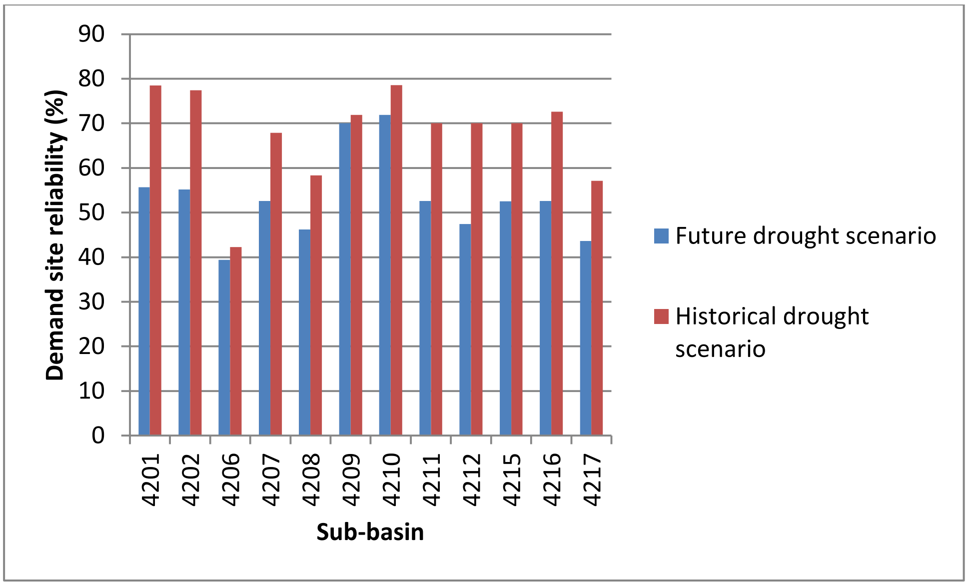


Figure 7.9: Comparison historical and future reliability of water resources to deliver water to sub-basin 's demand under reference and drought scenarios which is simulated by WEAP

7.3.1.4 Effect of future climate on crops

Between all human activities, agriculture is the greatest climate reliant. Developmentin predicting air-climate factor interaction with crop yield may benefit the agricultural sector by supporting farmers to alleviate or adjust to unfavourable climate circumstances. In this study, to analyse the effect of climate on agriculture, the association between temperature and crop yield was examined and it is useful for adaptation scenarios based on crop pattern change, which is explained in section 7.3.2.2.3.

Among climate factors temperature is used, because as Mohammad Bannayan et al., 2011 mentioned: temperature is the core of climate factors which show how climate influences the growth and yield of crops. For this purpose, linear correlation and scatterplots are used to understand the relationship. The association between yearly maximum temperature and historical crop yield was evaluated. Then with a linear regression method, the future relationship is forecasted. The analysis (Figure 7.10) shows that both rice and potato crop yield being highly correlated (R2=0.98 and R2=0.47) with maximum temperature in summer and autumn (growing season). In addition, a downward linear trend shows that with increasing temperature, the rice and potato crop yields are decreased. However, there is no specific correlation between wheat and barley yield with maximum temperature (R2= 0.37 and R2= 0.11). This means wheat and barley crops are less sensitive to temperature.

Although, in Iran, warmer daytime temperatures are likely to have declined rainfed and irrigated crops, Figure 7.11 illustrates that wheat and barley are more productive than rice and potato in years with maximum temperature.

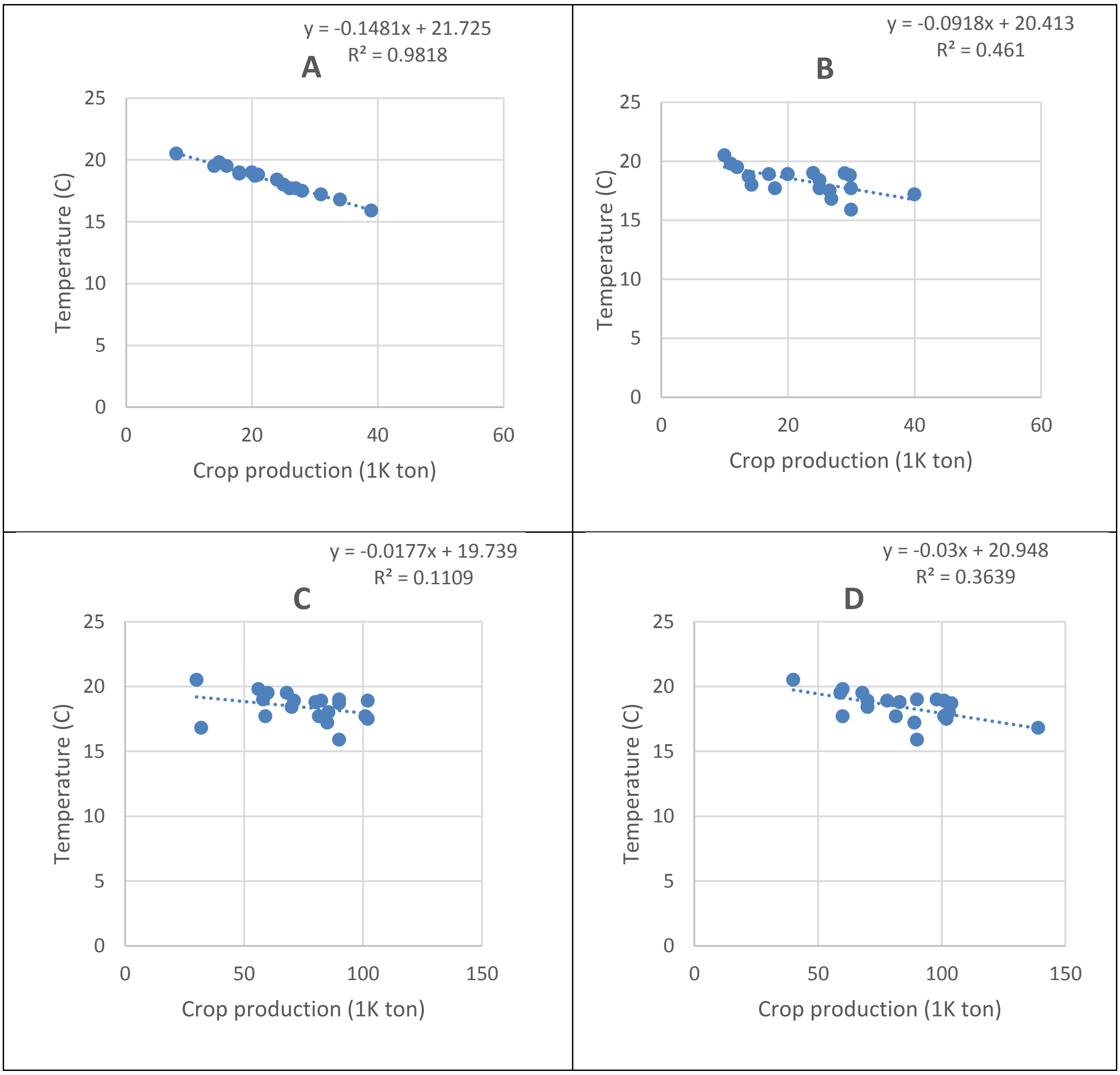


Figure 7.10: Scatter plot for relations between temperature and annual crop productions for the period of 1986-2006. (A) shows the relationship between rice. (B) Indicates the association for potato. However (C) and (D) represents the relationship between wheat and barley.

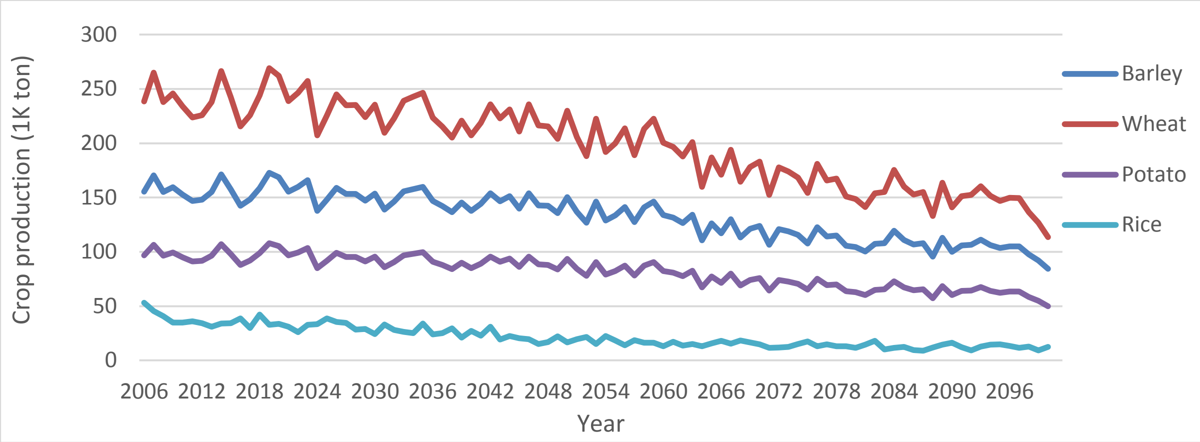


Figure 7.11: Projection of future crop productions (2006-2100)

7.3.2 Establishment of the adaptation scenarios

The influences of climate change and collaboration with other operators (especially during drought periods) can be used to make an adaptation strategy. A simulation model of WEAP is used to examine the changes in drivers that less affect water availability.

As mentioned previously, current water allocation policies say that domestic and industrial demands have first and second priority to use water. Agriculture and environment demands have the last priorities. These policies were entered into the WEAP model to determine possible water shortage and unmet demands during future periods.

However, agriculture is the main water user and uses 82% of the water resources in the basin. This demand is expected to increase in future and with no new source of water for trans-basin transfer, adaptation strategies are necessary to be established. The range of reservoir storage is restricted because of lower inflows and advanced demands. In order to avoid large failures in the water supplies system, water managers will need to investigate adjustment of their current water management practices to alleviate the negative results of less available water supplies.

7.3.2.1 Adaptation result from scenario for water resources

The assumption of this scenario is that two alternative volumes of water will transfer to the Zayandeh Rud basin from the neighbouring basin (Chaharmahal Bakhtiari basin). Furthermore, it is assumed that two alternative small dams will be constructed upstream and add to the hydrology system. It is assumed that two new tunnels from the neighbouring basin will transfer 230 and 580 MCM per year to the Zayandeh Rud basin. The assumption of the storage capacity of the two small dams is 18.2 and 17.1 MCM. This scenario was recommended by Esfahan Water Authority (EWA) in 2012. It assumes that construction of the dams causes less potential for evaporation and may cause decreasing in net evaporation through regulation rules. Because in Zayandeh Rud basin flow ends in Gawkhoni wetland where evaporation is very high, so, constructions the new dams in upstream with floating cover can cause less evaporation. Also it is expected the dams with true regulation for water release can save water when the demands are low (April to July). However, they can release water when there are maximum demands (especially during August to December while the unmet demands are high).

Table 7.2: Details of the future conceptual dams in the Zayandeh Rud basin

Dam 1	**Dam 2**
✓ Area: 2650 ha ✓ Volume: 18.2 MCM ✓ Location: Upstream, on river Khorbe in sub-basin 4216 Operation rules: ✓ No losses to groundwater ✓ Top of buffer zone (dam volume lower that delivery is limited): 9.1 MCM ✓ Top of inactive zone (dam volume lower that water is not accessible for distribution: 1.45MCM ✓ Buffer coefficient (portion of water in the buffer zone accessible for distribution every month): 0.8	✓ Area: 2150 ha ✓ Volume: 17.1 MCM ✓ Location: Upstream, on river Nal eshkanan in sub-basin 4216 Operation rules: ✓ No losses to groundwater ✓ Top of buffer zone (dam volume lower that delivery is limited): 8.6 MCM ✓ Top of inactive zone (dam volume lower that water is not accessible for distribution: 1.37MCM ✓ Buffer coefficient (portion of water in the buffer zone accessible for distribution every month): 0.8

To evaluate the impact of adaptation scenarios with new water resources and for other adaptation scenarios, the volume of the water storage in the Zayandeh Rud reservoir downstream of the conceptual dams, is analysed.

Figure 7.12 indicates the adaptation scenario with new water resources causes the monthly average storage volume during dry years to increase 2.91 times more than the scenario without any adaptation.

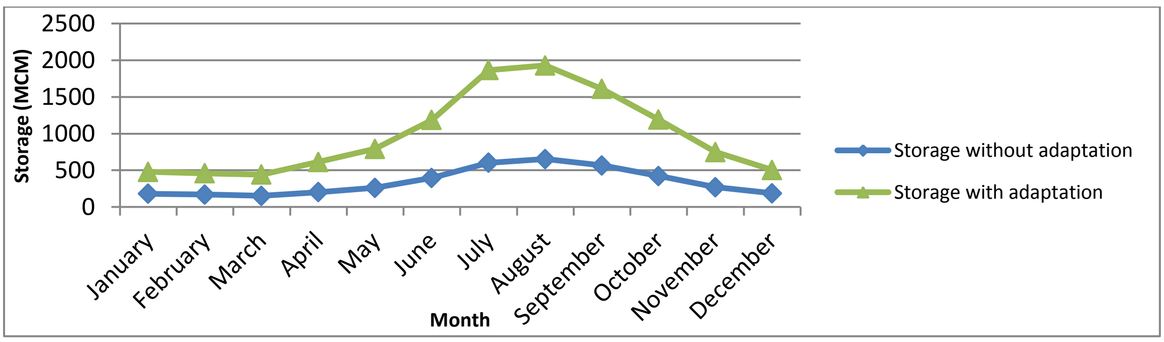


Figure 7.12: Comparison monthly average of Zayandeh Rud storage dam with and without adaptation of new water resources in future dry periods (2006-2100)

Figure 7.13 represents the adaptation scenario; the unmet demand will decrease in all consumer water sectors for all months, especially during summer and autumn months. In total, the average of unmet demands for the whole Zayandeh Rud will decrease 159MCM in comparison with the unmet demands value with no adaptation scenario.

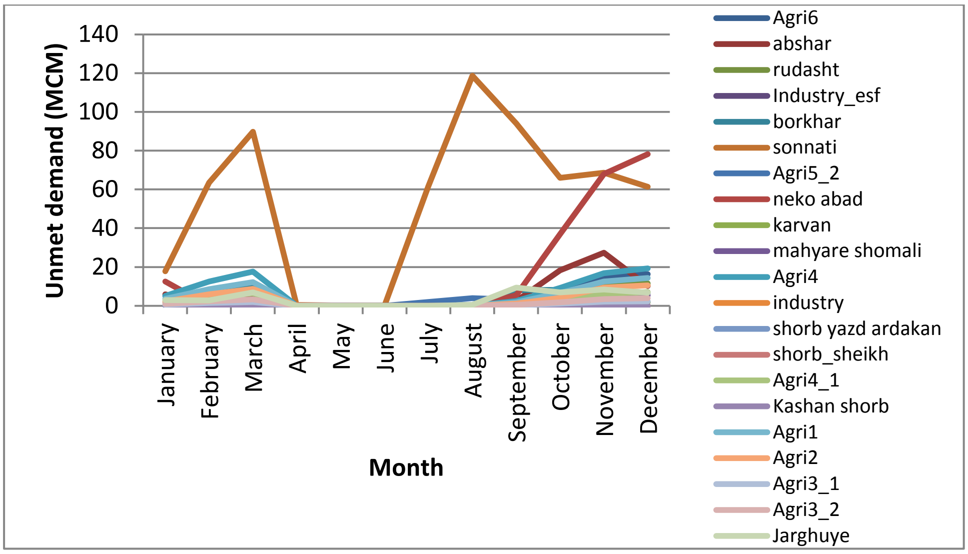


Figure 7.13: Total volume of unmet demands based on adaptation scenario with new water resources in the Zayandeh rub basin

Table 7.3 shows the simulated results of unmet demands and reliability of the system with the adaptation scenario during dry years. With this adaptation scenario, total unmet demand for all water users will decrease 54% (1701 MCM) in the Zayandeh Rud basin. In addition, the reliability of all demand sites is increased. The average reliability for the whole Zayandeh Rud basin is increased about 11% in comparison with no adaptation.

Table 7.3: Analysis unmet demand and reliability of the demand site in each sub-basin. The symbol of " *" indicates the sector is agricultural. Also, a symbol of "" shows the industrial user. However, the symbol of " ***" represent the domestic user.**

Sub-basin	water user sector (name)	Demand(MCM)	Unmet demand(MCM)	Reliability (%)	Overall reliability(%)
4201	Agri 6*	476.3854	59.27	52	61
	Abshar*	210.6536	64.41	65	
	Rudasht*	137.1965	29.62	66	
4202	Industry-esf**	400	0.17	99	58
	Borkhar*	736.5873	52.24	49	
	Sonnati*	782.1102	641.02	25	
4206	Agri5-2*	28.85771	20.99	25	49
	Neko-abad*	650.6105	205.33	60	
4207	Karvan*	76.42956	14.01	60	60
4208	Mahyar-shomali*	53.50388	19.63	52	52
4209	Agri 4*	284.94	82.65	52	87
	Industry**	432	2.38	98	
	Shorb Yazd ardekan***	55	0.37	98	
	Shorb Sheikh***	249	1.75	98	
4210	Agri 4-1*	211.6868	30.08	52	75
	Kashan shorb***	7.9	0.51	98	
4211	Agri 3-1*	182.1206	9.71	57	57
4212	Agri 2*	445.4453	41.91	50	50
4215	Agri 3-2*	62.575	16.28	57	57
4216	Agri 1*	359.3061	59.25	57	57
4217	Jarghoye*	540.5444	44.22	49	49

Figure 7.14 represents that with this scenario, for all sub-basins, the percentage of the reliability of the demand site increases. Also all unmet demands decrease, especially in the sub-basin that has the significant water consumers such as sub-basin 4202.

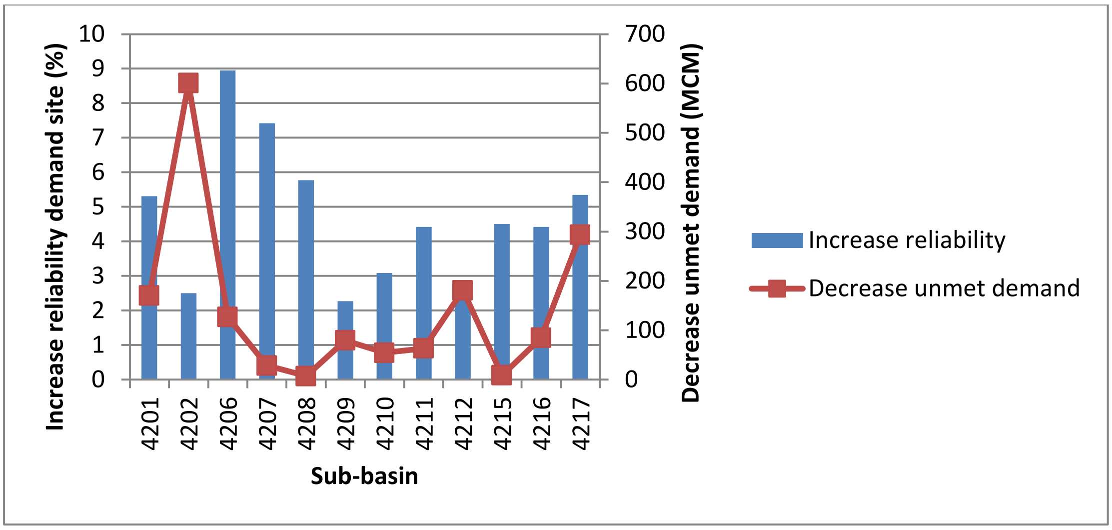


Figure 7.14: Increasing reliability of the demand sites and decreasing unmet demands with the adaptation scenario of new water resources against no adaptation scenario in the sub-catchments in Zayandeh rub basin.

7.3.2.2 Adaptation result from scenario for water demand and conservation

Three possible scenarios based on water demand management estimations consider the theoretical assumptions made by the Ministry of Energy in Iran on the potential saving that may be implemented if water conservation water demand management planning is fulfilled.

7.3.2.2.1 Scenario based on establishment of new irrigation technology

The new irrigation technology scenario is simulated by applying a WEAP model for a future drought scenario. According to (FAO, 2002), compared to surface irrigation or flooding irrigation, sprinklers and drip systems can provide 75 per cent efficiency Irrigation efficiency's value increases 41% in each irrigated area in each sub-basin and the scenario simulates efficiencies that can be achieved by sprinkler and drip irrigation methods. The average water uses' efficiency of all irrigation systems in the Zayandeh Rud basin is 34%, so with this scenario it will increase to 75%. It expected this scenario will produce results instantly compared to other scenarios that may take time to apply. Therefore, it should be noted that this adaptation scenario may be too useful to mitigate impacts of future droughts.

In this scenario, domestic and industrial demands will not change. However, the agricultural demands will reduce as shown in Table 7.4. In addition, the storage volume will decline less as represented in Figure 7.15, and the unmet demand can decrease (Figure 7.16).

Figure 7.15 indicates the adaptation scenario 2 (establishment of new irrigation technology) will cause the monthly average storage volume during dry years to increase 1.43 times more than the scenario without any adaptation.

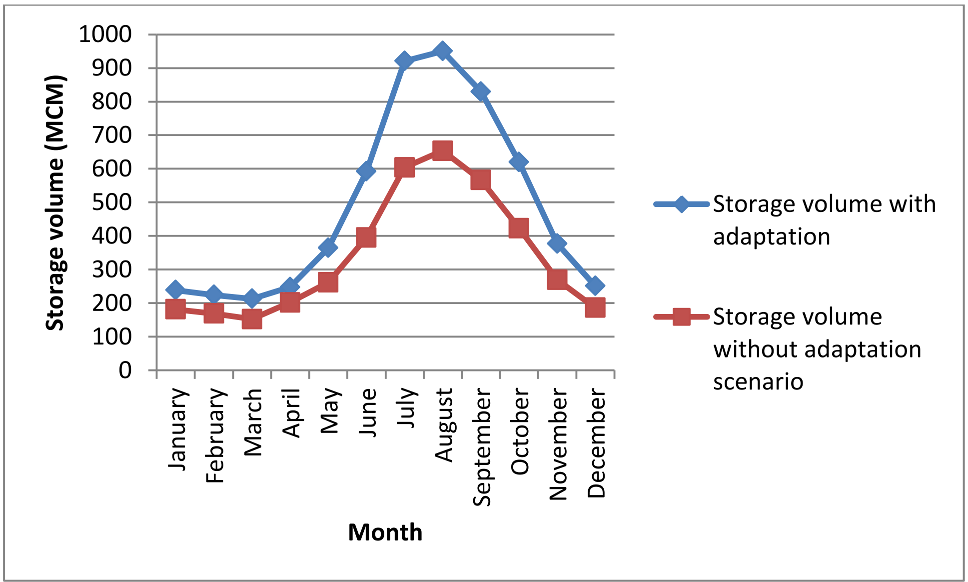


Figure 7.15: Comparison monthly average of Zayandeh Rud storage dam with and without adaptation of developing irrigation efficiency in future dry periods (2006-2100)

Figure 7.16 represents the adaptation scenario; the unmet demand will decrease in all consumer water sectors for all months, especially during summer and autumn months (August to December) when the hydrological droughts are significant. In total, the average unmet demands for the whole Zayandeh Rud will decrease 120 MCM in comparison with the unmet demands' value with no adaptation scenario.

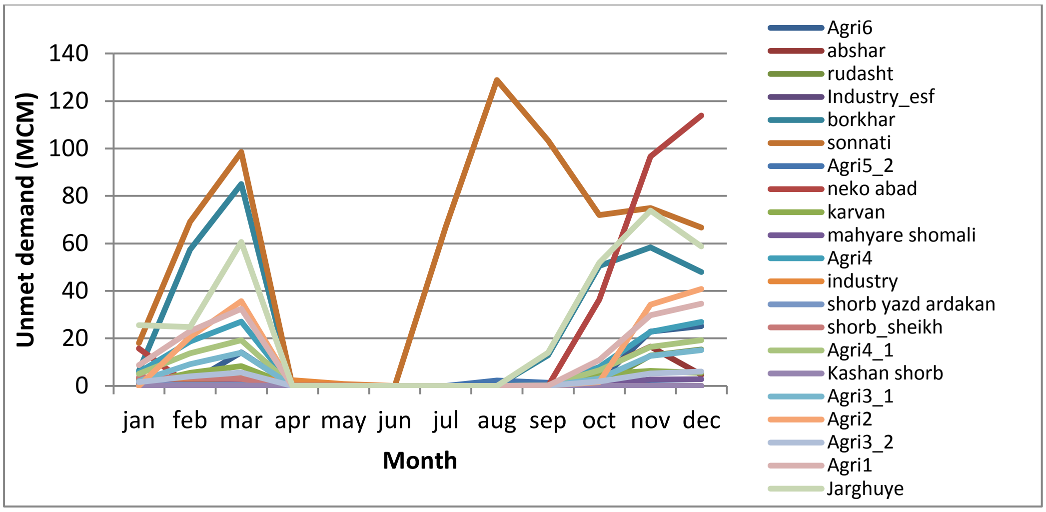


Figure 7.16: Total volume of unmet demands based on adaptation scenario with developing irrigation efficiency in the Zayandeh rub basin

Table 7.4 shows the simulating results of unmet demands and reliability of the system with the adaptation scenario during dry years. With this adaptation scenario, total unmet demand for all water users will decrease 15% (366 MCM) in the Zayandeh Rud basin. In addition, the reliability of all demand sites is increased. The average reliability for whole of the Zayandeh Rud basin is increased about 6% in comparison with no adaptation.

Table 7.4: Analysis unmet demand and reliability of the demand site in each sub-basin with adaptation scenario of developing irrigation efficiency. The symbol of " *" indicates the sector is agricultural. Also, a symbol of "" shows the industrial user. However, the symbol of " ***" represent the domestic user.**

Sub-basin	water user sector	Demand(MCM)	Unmet demand(MCM)	Reliability (%)	Overall reliability
	Agri 6*	357	105	57.53	
	Abshar*	90	37.97468	70.63	
4201	Rudasht*	97	45.11628	71	66.38666667
	Industry-esf**	400	118	99.4	
	Borkhar*	697	400.5747	54.56	
4202	Sonnati*	740	711.5385	28	60.65333333
	Agri5-2*	24.85	23.89423	28	
4206	Neko-abad*	559	279.5	65	46.5
4207	Karvan*	67.94	37.74444	63	52.58
4208	Mahyar-shomali*	20	10	59	46.23
	Agri 4*	239	119.5	58	
	Industry**	432	12.38	98.21	
	Shorb Yazd ardekan***	55	1.12	98.8	
4209	Shorb Sheikh***	249	10.69	98.8	88.4525
	Agri 4-1*	199	79.6	57.53	
4210	Kashan shorb***	7.9	0.25	98.41	77.97
4211	Agri 3-1*	172.12	68.848	63	52.58
4212	Agri 2*	386	193	55	47.42
4215	Agri 3-2*	58.57	23.428	62.1	52.5
4216	Agri 1*	349	139.6	54.96	52.58
4217	Jarghoye*	421	309.5588	54.56	43.65

Figure 7.17 represents that with this scenario, for all sub-basins the percentage of the reliability of the demand site increases. Also all unmet demands decrease, especially in the sub-basin that has the significant water consumers such as sub-basin 4202. However compared to the adaptation scenario 1, the increased reliability and decreased unmet demand is lower. For example for the sub-catchment 4202 with adaptation scenario 1 the decrease of unmet demands is 600 MCM but with the adaptation scenario 2 the value is only 70 MCM.

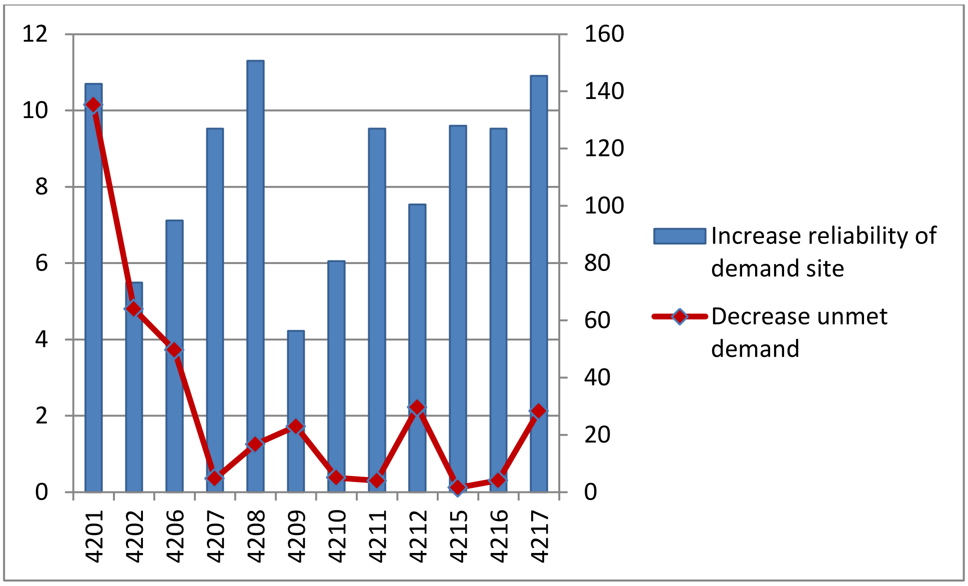


Figure 7.17: Increasing reliability of the demand sites and decreasing unmet demands with the adaptation scenario of developing irrigation efficiency against no adaptation scenario in the sub-catchments in Zayandeh rub basin.

7.3.2.2.2 Scenario based on decreasing crop area

Decreasing all cropped areas is one of the achievable adaptation strategies. The scenario can give an outlook to water managers and decision makers that through the decreasing of 40% of significant irrigated area, the water stress will reduce during dry years. The agricultural water requirements for major crops i.e. rice, wheat, barley and potato will reduce as represented in Table 7.5. However, the domestic and industrial demands will remain the same. The Zayandeh Rud storage volume and unmet demands are shown in Figures 7.18 and 7.19.

Figure 7.18 indicates the adaptation scenario 3 (decreasing crop area) causes the monthly average storage volume during dry years to increase 1.42 times more than the scenario without any adaptation.

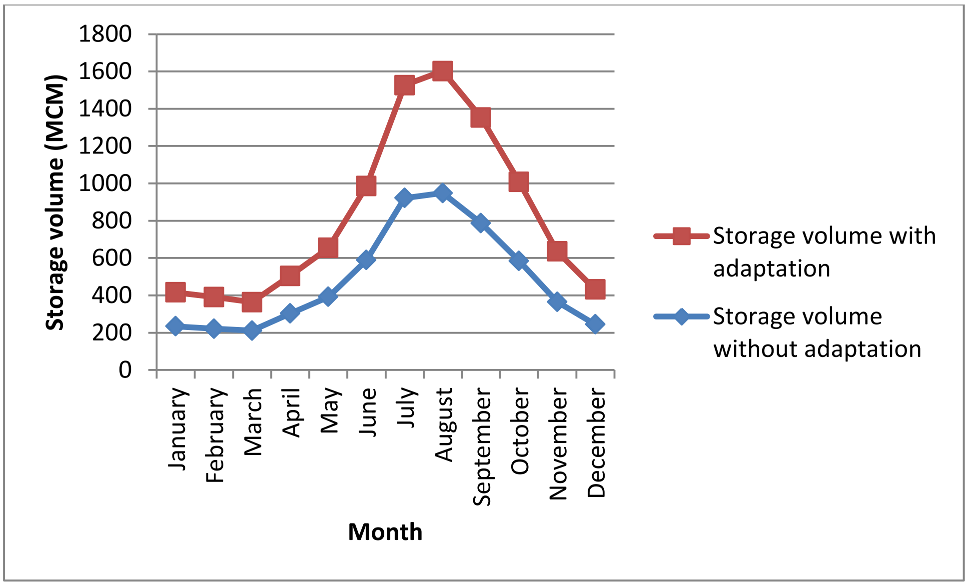


Figure 7.18: Comparison monthly average of Zayandeh Rud storage dam with and without adaptation of decreasing crop area in future dry periods (2006-2100)

Figure 7.19 represents the adaptation scenario; the unmet demand will decrease in all consumer water sectors for all months, especially during summer and autumn months. In total, the average unmet demands for the whole Zayandeh Rud will decrease 77 MCM in comparison with the unmet demands' value with no adaptation scenario.

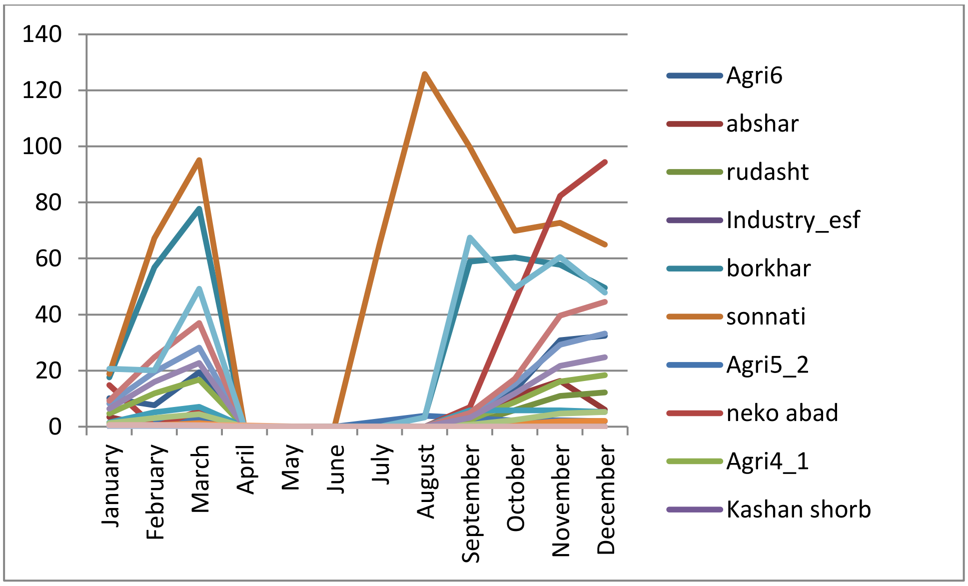


Figure 7.19: Total volume of unmet demands based on adaptation scenario with decreasing crop area in the Zayandeh rub basin

Table 7.5 shows the simulating results of unmet demands and reliability of the system with the adaptation scenario during dry years. With this adaptation scenario, total unmet demand for all water users will decrease 8% (228 MCM) in the Zayandeh Rud basin. The average reliability for the whole Zayandeh Rud basin is increased about 4% in comparison with no adaptation.

Table 7.5: Analysis unmet demand and reliability of the demand site in each sub-basin with adaptation scenario of changing crop area. The symbol of " *" indicates the sector is agricultural. Also, a symbol of "" shows the industrial user. However, the symbol of " ***" represent the domestic user.**

Sub-basin	Water user sector	Demand (MCM)	Unmet demand (MCM)	Reliability (%)	Overall reliability
4201	Agri 6*	459	163.9286	51.98413	60.64815
	Abshar*	155.6	65.65401	64.88095	
	Rudasht*	98	45.5814	65.07937	
4202	Industry-esf**	400	118	99.4	57.93757
	Borkhar*	698	401.1494	48.4127	
	Sonnati*	744	715.3846	26	
4206	Agri5-2*	26	25	25	42.06349
	Neko-abad*	574	287	59.12698	
4207	Karvan*	70.72	39.28889	56.54762	62.1
4208	Mahyar-shomali*	35	17.5	51.98413	46.23
4209	Agri 4*	248.9	124.45	51.98413	86.94853
	Industry**	432	12.38	98.21	
	Shorb Yazd ardekan***	55	1.12	98.8	
	Shorb Sheikh***	249	10.69	98.8	
4210	Agri 4-1*	203	81.2	51.98413	75.19841
	Kashan shorb***	7.9	0.25	98.4127	
4211	Agri 3-1*	176	70.4	56.54762	52.58
4212	Agri 2*	400	200	49.20635	47.42
4215	Agri 3-2*	60	24	56.54762	52.5
4216	Agri 1*	356	142.4	56.54762	52.58
4217	Jarghoye*	436	320.5882	48.4127	43.65

Figure 7.20 represents that with this scenario, for all sub-basins, the percentage of the reliability of the demand site increases. Also all unmet demands decrease, especially in the sub-basin that has the significant water consumers such as sub-basin 4202. However, compared to the adaptation scenarios 1 and 2, the increased reliability and decreased unmet

demand is lower. For example for the sub-catchment 4202 with adaptation scenario 1 the decreased unmet demands is 600 MCM and with the adaptation scenario 2 the value is only 70 MCM. While the decreasing in unmet demand for this adaptation scenario is 60 MCM.

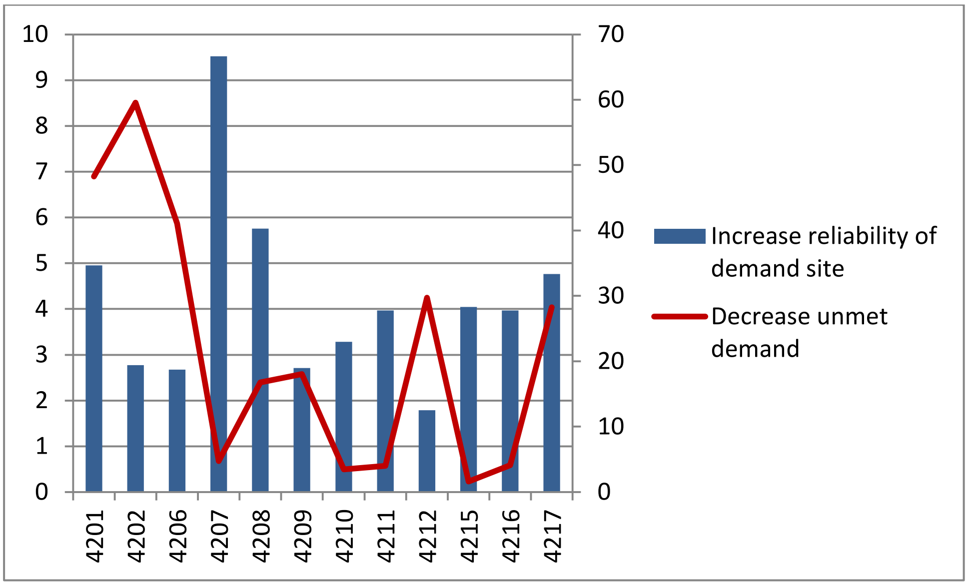


Figure7.20: Increasing reliability of the demand sites and decreasing unmet demands with the adaptation scenario of decreasing crop area against no adaptation scenario in the sub-catchments in Zayandeh rub basin.

This scenario is difficult to fulfil immediately and it may have unfavourable influences on the socio-economic problems that will occur due to declining agricultural income and fewer employment opportunities. The negative influences probably can be reduced by providing jobs in the industry sections that need less water.

7.3.2.2.3 Scenario based on crop pattern change

This scenario depends on exchanging rice with wheat and potatoes with barley. The wheat and barley need less water in comparison with rice and potatoes. In addition, the energy produced and crop yields of wheat and barley are 3 to 6 times greater than for rice and potatoes. The agricultural requirements will decline more as illustrated in Table 7.6. However, the urban demands and all other water consumers will stay the same. The unmet demands have been developed in comparison with the scenarios without adaptation. The analysis of the modelling for this scenario indicates that replacing rice with wheat and potatoes with barley will decrease water stress and have positive influences on increasing the storage volume of the Zayandeh Rud dam during the dry period. Therefore, by substituting the crop patterns, it is possible to allocate more water for agricultural sectors and store it for dry periods. Figure 7.21 indicates that adaptation scenario 4 (changing crop pattern) causes the monthly average storage volume during dry years to increase 1.45 times more than the scenario without any adaptation.

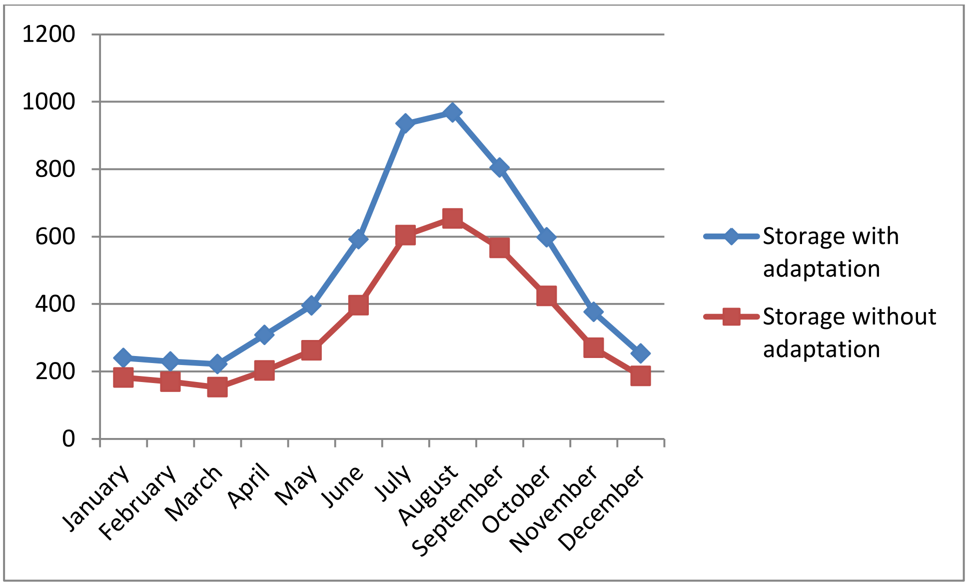


Figure 7.21: Comparison monthly average of Zayandeh Rud storage dam with and without adaptation of changing crop pattern in future dry periods (2006-2100)

Figure 7.22 represents the adaptation scenario; the unmet demand will decrease in all consumer water sectors for all months, especially during summer and autumn months. In total, the average unmet demands for the whole Zayandeh Rud will decrease 142 MCM in comparison with the unmet demands' value with no adaptation scenario.

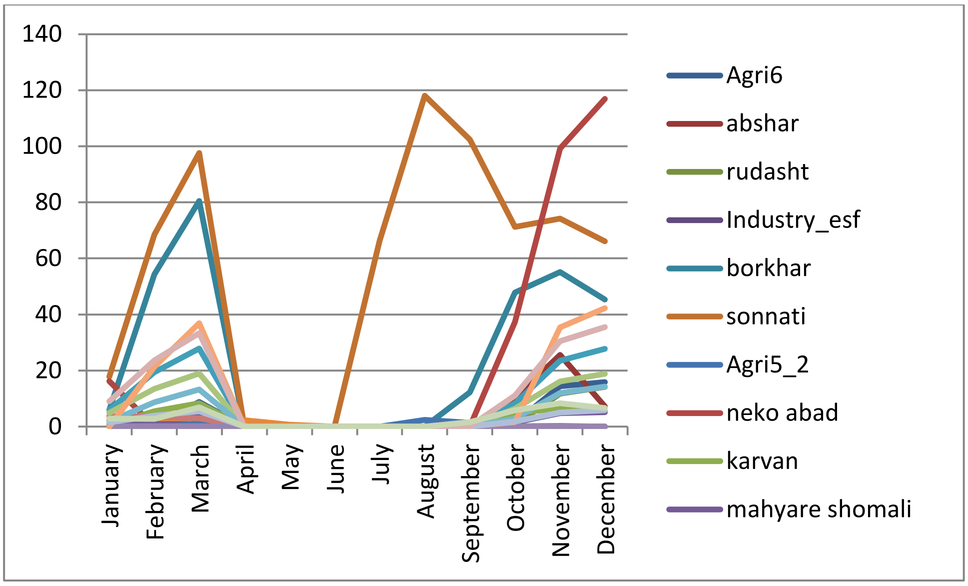


Figure 7.22: Total volume of unmet demands based on adaptation scenario with changing crop patterns in the Zayandeh rub basin

Table 7.6 shows the simulating results of unmet demands and reliability of the system with the adaptation scenario during dry years. With this adaptation scenario, total unmet demand for all water users will decrease 19% (1032 MCM) in the Zayandeh Rud basin. The average reliability for the whole Zayandeh Rud basin is increased about 8% in comparison with no adaptation.

Table 7.6: Analysis unmet demand and reliability of the demand site in each sub-basin with adaptation scenario of changing crop pattern. The symbol of " *" indicates the sector is agricultural. Also, a symbol of "" shows the industrial user. However, the symbol of " ***" represent the domestic user.**

Sub-basin	Water user sector	Demand (MCM)	Unmet demand (MCM)	Reliability (%)	Overall reliability
4201	Agri 6*	350	125	59.98	67.32667
	Abshar*	90	37.97468	70	
	Rudasht*	70	32.55814	72	
4202	Industry-esf**	400	118	99.4	63.46667
	Borkhar*	662	380.4598	56	
	Sonnati*	708	680.7692	35	
4206	Agri5-2*	21.4	20.57692	35	51
	Neko-abad*	499	249.5	67	
4207	Karvan*	62.47	34.70556	63	63
4208	Mahyar-shomali*	15	7.5	59.98413	59.98413
4209	Agri 4*	212	106	59.98413	88.94853
	Industry**	432	12.38	98.21	
	Shorb Yazd ardekan***	55	1.12	98.8	
	Shorb Sheikh***	249	10.69	98.8	
4210	Agri 4-1*	197	78.8	59.98413	79.19841
	Kashan shorb***	7.9	0.25	98.4127	
4211	Agri 3-1*	169	67.6	64	64
4212	Agri 2*	355	177.5	57	57
4215	Agri 3-2*	56.35	22.54	64	64
4216	Agri 1*	347	138.8	65	65
4217	Jarghoye*	430	316.1765	56	56

Figure 7.23 represents that with this scenario, for all sub-basins, the percentage of the reliability of the demand site increases. Also all unmet demands decrease, especially in the sub-basin that has significant water consumers such as sub-basin 4202. However, compared to the adaptation scenario 1, the increased reliability and decreased unmet demand is lower. For example for the sub-catchments 4202 with adaptation scenario 1 the decreased unmet demands is 600 MCM but with the adaptation scenario 4 the value is 120 MCM. However, compared with adaptation scenarios 2 and 3 the decreasing unmet demand in scenario 4 is

higher and more significant. The decreased unmet demand under adaptation scenarios 2 and 3 is only 70 and 60 MCM.

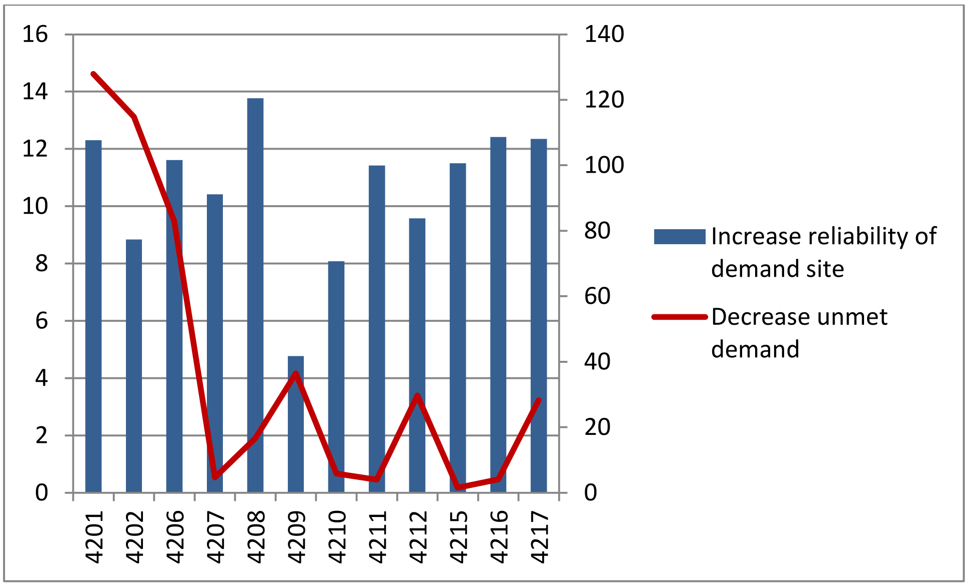


Figure 7.23: Increasing reliability of the demand sites and decreasing unmet demands with the adaptation scenario of crop pattern changes against no adaptation scenario in the sub-catchments in Zayandeh rub basin.

7.3.2.2.4 Combination of the scenarios

If all previous scenarios combine, it causes the monthly average storage volume during dry years to increase 5 times more than the scenario without any adaptation (Figure 7.24).

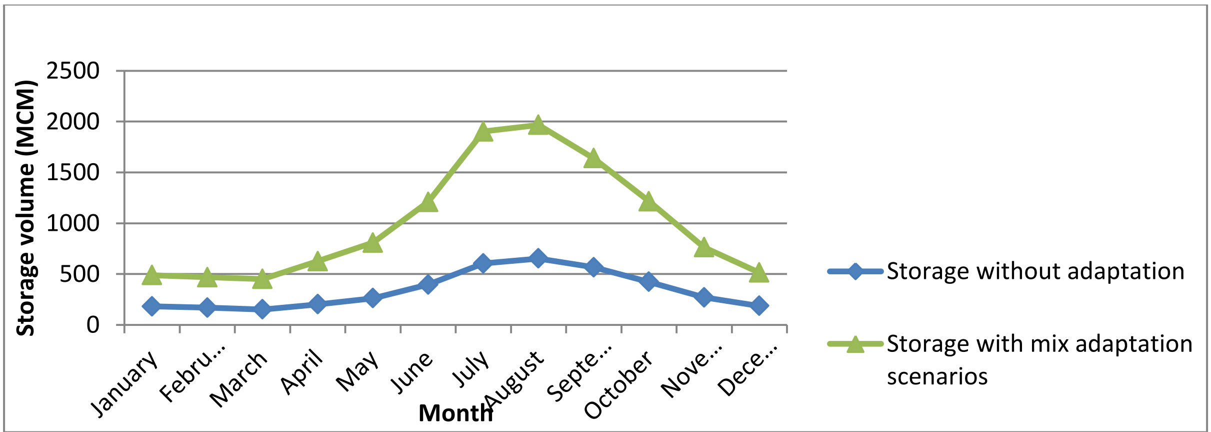


Figure 7.24: Comparison monthly average of Zayandeh Rud storage dam with and without mix adaptation scenarios in future dry periods (2006-2100)

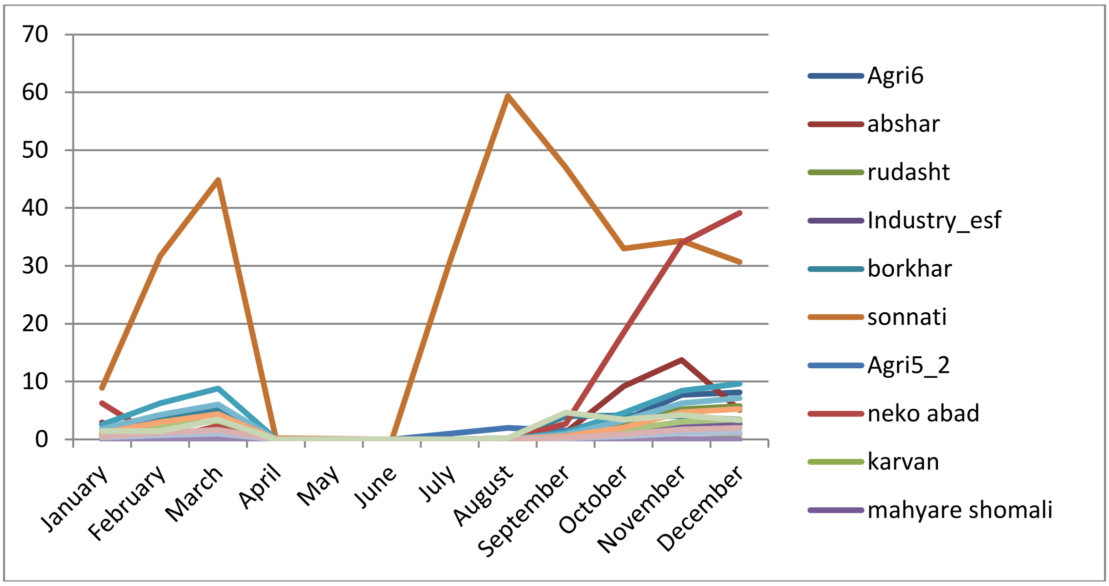


Figure 7.25: Total volume of unmet demands based on combination of all adaptation scenarios in the Zayandeh rub basin

Figure 7.25 represents that with a mix adaptation scenarios; the unmet demand will decrease in all consumer water sectors for all months, especially during summer and autumn months. In total, the average unmet demands for the whole Zayandeh Rud will decrease 705 MCM in comparison with the unmet demands' value with no adaptation scenario.

Table 7.7 shows the simulating results of unmet demands and reliability of the system with the mix adaptation scenarios during dry years. With the mix adaptation scenarios, total unmet demand for all water users will decrease 61% (2068 MCM) in the Zayandeh Rud basin. The average reliability for the whole Zayandeh Rud basin is increased about 21% in comparison with no adaptation.

Table 7.7: Analysis unmet demand and reliability of the demand site in each sub-basin with adaptation scenario of changing crop pattern. The symbol of " *" indicates the sector is agricultural. Also, a symbol of "" shows the industrial user. However, the symbol of " ***" represent the domestic user.**

Sub-basin	water user sector (name)	Demand(MCM)	Unmet demand(MCM)	Reliability (%)	Overall reliability(%)
4201	Agri 6*	376.3854	39.51333333	62	74
	Abshar*	110.6536	42.94	75	
	Rudasht*	37.1965	19.74666667	76	
4202	Industry-esf**	300	0.113333333	100	69
	Borkhar*	636.5873	34.82666667	59	
	Sonnati*	682.1102	427.3466667	35	
4206	Agri5-2*	10	13.99333333	35	60
	Neko-abad*	550.6105	136.8866667	70	
4207	Karvan*	10	9.34	70	70
4208	Mahyar-shomali*	20	13.08666667	62	63
4209	Agri 4*	184.94	55.1	62	98
	Industry**	332	1.586666667	100	
	Shorb Yazd ardekan***	20	0.246666667	100	
	Shorb Sheikh***	149	1.166666667	100	
4210	Agri 4-1*	111.6868	20.05333333	62	88
	Kashan shorb***	7	0.34	100	
4211	Agri 3-1*	82.1206	6.473333333	67	68
4212	Agri 2*	345.4453	27.94	60	60
4215	Agri 3-2*	20	10.85333333	67	67
4216	Agri 1*	259.3061	39.5	67	68
4217	Jarghoye*	440.5444	29.48	59	59

7.4 Discussion

The results of this research indicate one specific climate change scenario (RCP 8.5) derived from one set of the model will affect the basin water resources and water demands.

Under the climate change scenario, the HadCM3 model predicts a decrease in mean annual rainfall for 2006-2100. Association with a prediction increases the potential evapotranspiration; this converts into a reduction in average annual basin flow consequently. The Zayandeh Rud river basin is likely to face more deficits in stream flows; so more demands will be affected by the negative impacts of the deficit unless the adaptation strategies are established. The results in this chapter show other water resources and groundwater recharges are predicted to decline during future drought periods. Therefore, climate-driven impacts on surface water supplies, groundwater storage and specifically irrigation demands are anticipated to be significant under a projected warmer and drier climate especially under the scenario of RCP 8.5 in a future period.

Future drought management requires incorporating long-term strategies for water management coordinating, developing early warning and monitoring systems (Wilhite and Buchanan-Smith, 2005). Monitoring and early warning of potential water quantity and the impacts on water demands are a key element of the plan.

Improvement and continuing to make a model that shows development in technology and water management plays an important role for accounting for water resources (Wilhite et al., 2007).

Scientific approaches to measuring variations of the climate system and their impacts offer an opportunity to improve prediction methods to develop adaptation strategies.

Unlike previous research (Rajbhandari et al., 2015) on a semi arid river basin (Indus river basin) which shows that climate change causes increased river flow and flash flooding, in this research the result indicates climate change causes decreasing river flow and hence decreased volume of water available.

Agriculture in the basin depends on rainfall and surface river flow significantly. Anticipated less rainfall and larger human abstractions will lead to more droughts and dry spells which are likely affect crop seasons and decrease the flexibility of farmers.

Some recent research (Giordano and Villholth, 2007, Tuinhof et al., 2011) called for agricultural water use to command a possible alteration to groundwater due to insufficient natural rainfall. However, groundwater storage cannot compensate for the demands in arid or semi-arid regions because a decreasing trend in groundwater storage causes unsustainable conditions especially in the region which sometimes consumes water resources illegally.

In addition, the results of this study revealed differences in the association between climate factors and crop yields. The temperature plays an important role in the failure or success of the crop yield. However, such associations have not been measured for the provision of food security. For example, a previous study (Soltani and Hoogenboom, 2007) only analysed the relationship between monthly rainfall and maize in central and southern Iran. Another example is research of (Jury et al., 1997) which investigates the relationship between ENSO, rainfall and barley and maize crop yield in Africa and Mexico for a historical period.

This study is the first research in the middle east area that analyses the relationship between temperature and crop yields on a local scale and use the consequences to predict future crop yields. The results show that there is a high relationship between rice and potato yield with maximum temperature and with increasing temperature, the yield decreases. However, wheat and barley yield did not show a specific correlation with maximum temperature. So it can be understood a wheat and barley yield will more suitable for this area, which can help the economics of farmers enormously as with increasing temperature, their yield will not decrease dramatically.

In this study, with making possible adaptation scenarios, the ability of the water resources to meet the demands is investigated during future dry years. Unlike a previous study (Jha and Gupta, 2003) which used a Mike basin model or (Gonenc et al., 2014, Omar, 2013) studies which used a Ribasim model in Egypt as an adaptation strategy in the Mun River Basin, Thailand, the WEAP software is strong in running models for different scenarios and for comparison of the scenarios.

In agreement with previous research (Le Roy, 2005) on the Olifants catchment, South Africa which is an arid region, the function of the existing reservoir and dams is decreased by the predicted impact of climate change during drought. However, adaptation scenario 1 can raise water resources. The impact of new water resources upstream predicts increasing water volume downstream. In addition, it can be understood that scenario 1 inspects the consequences of an important basin water transfer from the neighbouring basin. The aim of this scenario was to highlight the advantages and disadvantages of the additional new dams and additional water transfer into the Zayandeh Rud basin during future drought periods.

Domestic and industrial demands are expected to rise because of a rising population rate in the basin; therefore they have the highest priority. However, under the current water management strategy, irrigation water demands from significant water consumers have the third priority in the basin. Without adaptation scenarios, 56% of the total irrigation demands cannot reach their water requirements.

To mitigate the impact of climate change, the adaptation scenarios can decrease the unmet demand during future drought periods as shown in Figure 7.27.

Scenario 2 is based on saving water used by developing irrigation efficiency. As shown in another study (Smits et al.) in Sand River Catchment in South Africa, new expenditure in the irrigation infrastructure and developing water management can decrease the impact of water scarcity during drought periods. As suggested in other studies (Amarasinghe et al., 2007, Bouwman, 1997), these scenarios determined a set of practices and investigated that most practices can either benefit unmet demand mitigation or adaptation to climate change. However, more extensive analysis of the complicated relationships is needed.

In line with other authors (De Vries and Wolf, 2015, Xie et al., 2014, Newton et al., 2013) in this research, from the results of adaptation scenario 3 with decreasing crop areas, it can be expected and assumed the CO2, NO2, and CH4 from diesel –powered mobile farm equipment can decrease (however the amount of this reduction is not estimated in this study). Thus, it can mitigate the impacts of climate change. Because the number of farmers which use diesel equipment is quite high in the basin (56 MJ per Lit) (Taki et al., 2012).

Furthermore with crop pattern changes in scenario 4, it can be concluded that a warmer climate in future will allow early planting and provide favourable conditions for wheat and barley. Previous research shows that warmer temperatures cause negative impacts on the growing of winter wheat and cereal rye. However this research shows that warmer temperature causes wheat and barley to grow well. Also, these crops following by the photosynthesis assumed that can use more CO_2 from the atmosphere and can decrease the effects of CO_2 emissions; while CO_2 from rice cultivation is higher than from wheat and barley (Schmitt et al., 1981) (however the amount of this reduction is not estimated in this study). Burning rice straw can cause an increase in CO_2. The field burning of rice straw is commonly practiced in regions in Asia such as the Zayandeh Rud basin. Emissions of CO_2 or other greenhouse gasses from agriculture that are important tools for adaptation strategies are not considered in most of the previous research i.e.(Jackson and Commission, 2012).

Adaptation scenarios in this chapter can help to develop the land use policies. Using smart policies that conserve existing farmland are likely to help preserve or decrease the impact of CO_2 emissions or climate change during future drought periods.

All adaptation scenarios can prevent the Zayandeh Rud reservoir being significantly dry in drought periods (Figure 7.26). As in previous research on the Guadiana Basin in Spain (Esteve et al., 2015), the adaptation plans (based on preserving environmental flows) can importantly reduce water demand. Specially if all adaptation scenarios combine, the storage of the Zayandeh rud reservoir will increase significantly and unmet demand will decrease dramatically.

However, results from agricultural demands should be viewed with caution; as even with the adaptation scenarios, all irrigation requirements will not be completely fulfilled. Maybe as (Burton, 2009, Lemmen and Bourque, 2008) mentioned in previous research on a region in Canada, additional adaptation plans should be established to decrease more unmet demands.

In this research, even with adaptation scenarios, irrigation demands suffer deficits in the range of 10-13% during dry years; but the unmet demands still decrease in comparison with having no adaptation scenario. With the adaptation scenarios, the reliability of the water resources will increase up to the year 2100 (Figure 7.28). Table 7.8 indicates the summary of future monthly average storage volume, unmet demands and the reliability of the system to deliver water to demand sites with and without adaptation scenarios. As shown in the table, mix adaptation scenario represents the highest storage volume and the greatest reliability of the system with the lowest unmet demands. However, adaptation scenario 3 indicates the lowest storage volume and the the lowest reliability of the system with the highest unmet demands.

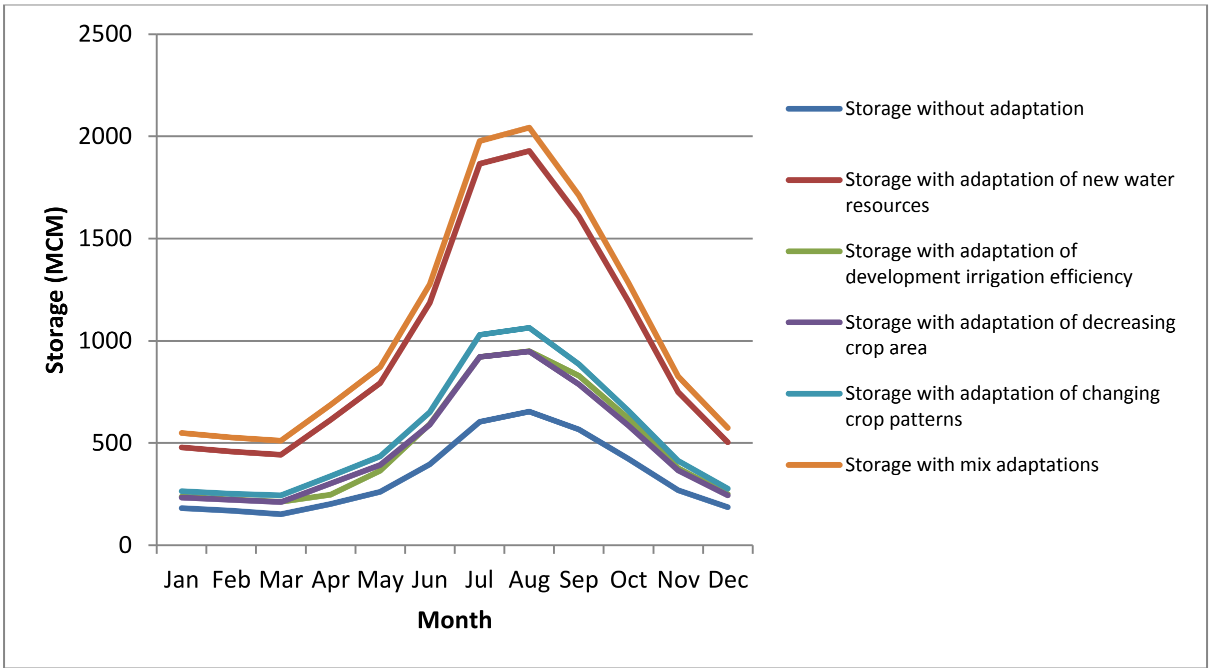


Figure 7.26: Storage of the Zayandeh Rud reservoir with and without all adaptation scenarios for future predicted dry years.

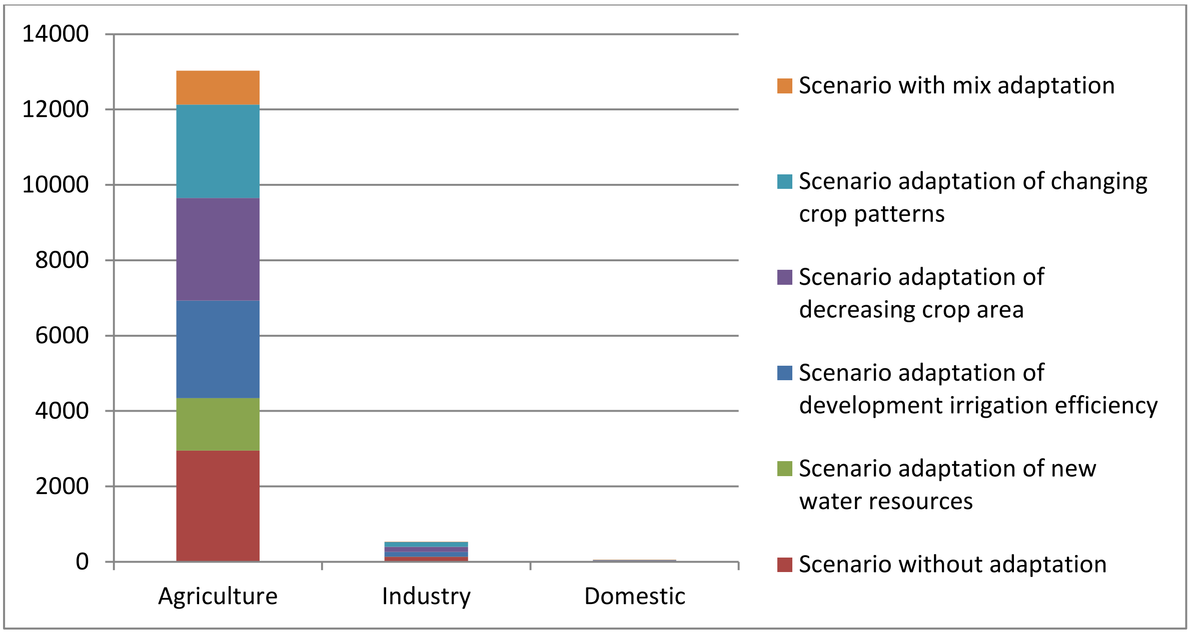


Figure 7.27: Future unmet demands under the adaptation scenarios during dry years

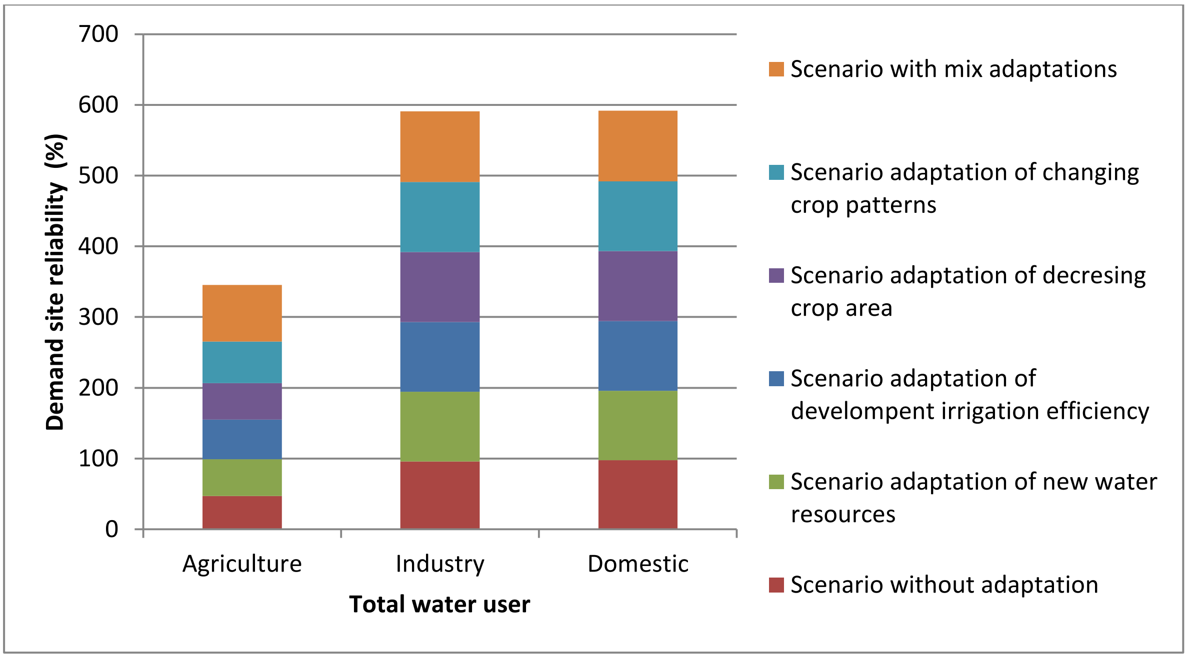


Figure 7.28: Demand site reliability with and without adaptation scenarios for future predicted dry years for the Zayandeh Rud river basin

Table 7.8: Monthly average comparison of storage volume of Zayandeh Rud reservoir, unmet demands and reliability of the water resources to deliver water to demand site, with and without adaptation scenarios.

Condition	Storage volume(MCM)	Unmet demand(MCM)	Demand site reliability(%)
Without adaptation	338.89	1031.18	70.26
Adaptation scenario 1	985.10	465.26	85
Adaptation scenario 2	485.81	909	82.91
Adaptation scenario 3	483.60	955.32	82.75
Adaptation scenario 4	493.14	872.60	84.61
Mix adaptation	1036.28	326.09	94

In agreement with the previous study (McCartney et al.) cooperation with the water management can provide awareness and a tool set for planning local integrated use policies to make changes in irrigation technology, crop areas and crop patterns. When water resources are managed at the river basin level, there is an opportunity to reply straightforwardly to policy decisions. Creating the adaptation scenarios in this chapter is not enough. The Government has a significant role in advancing flexibility in the water sector. The performance of the Government in the agricultural sector needs to contain:

1) Granting farmers clear information about the projected changes and possible influences on their current situation.
2) Providing farms with the tools to determine their future farming plans.
3) Creating development and educational training about how to make these changes.
4) Allowing new favourable circumstances to increase as a result of climate changes.

7.5 Conclusion

In this study, the WEAP hydrological model has been used to estimate climate change influences on both future water supply and demand and their potential impacts on water management strategies in the Zayandeh Rud river basin . The model was calibrated with historical data, and then by current and future climate conditions were used as data inputs from the CMIP5 model under the scenario of RCP8.5. The objective of the study was to evaluate whether the future water demand can be met by water resources in the basin with no change in current water management practices. The WEAP simulations were run by using climate change scenarios with and without adaptation strategies.

Four adaptation strategies were investigated. As seen in Figure 7.25, the unmet demand will be high in future in the absence of adaptation strategies; due to population growth and increased demand in higher per capita use rates . Addtionally, the decreasing inflow to the basin due to climate change willcompound the situation of insufficient water to meet future demands and use .

With implementing adaptation scenario 1, the volume of the Zayandeh Rud reservoir during dry years will 647 MCM higher than it would be when no adaptation was used in the river basin.

Using adaptation scenario 2, which included the consideration of irrigation efficiency, because it can optimise agricultural water supply needs for the climate change scenario. It also can potentially result in reduction in the average annual surface water deliveries to agriculture.

Adaptation scenario 3, creating a decrease in cropland, means that irrigation regions can be assured of a higher portion of their irrigation demands.

Adaptation scenario 4 suggests that irrigation water users in the basin can capture water savings as a result of decreasing consumptive demands in agricultural areas through replacing rice with wheat and potatoes with barley.

As shown in Figure 7.24, with adaptation scenarios 2,3 and 4, and a combination scenario agricultural demands will decrease and the deficit in the volume of the Zayandeh Rud reservoir will decrease.

It can be concluded that adjustment of agricultural requirements because of performance adaptation strategies to climate change, developed the reliability of surface water deliveries for the Zayandeh Rud basin. The future drought scenario indicated great differences from simulations being run with adaptations.

CHAPTER EIGHT: SYNTHESIS AND FUTURE RESEARCH

8.1 Introduction

The final chapter of this thesis explains the research gaps that were identified and advances the current understanding of drought and the association between various variables. It includes summaries of some of the major outcomes and the limitations of the study. Recommendations for future water managements strategies that cxan be taken up by government agencies and planning departments are presented Topics for further investigation has been outlined. The practical application of this work for water scarcity and drought management is highlighted. The conceptual model for the key elements of the thesis and summary of findings are shown in Figures 8.1 and 8.3.

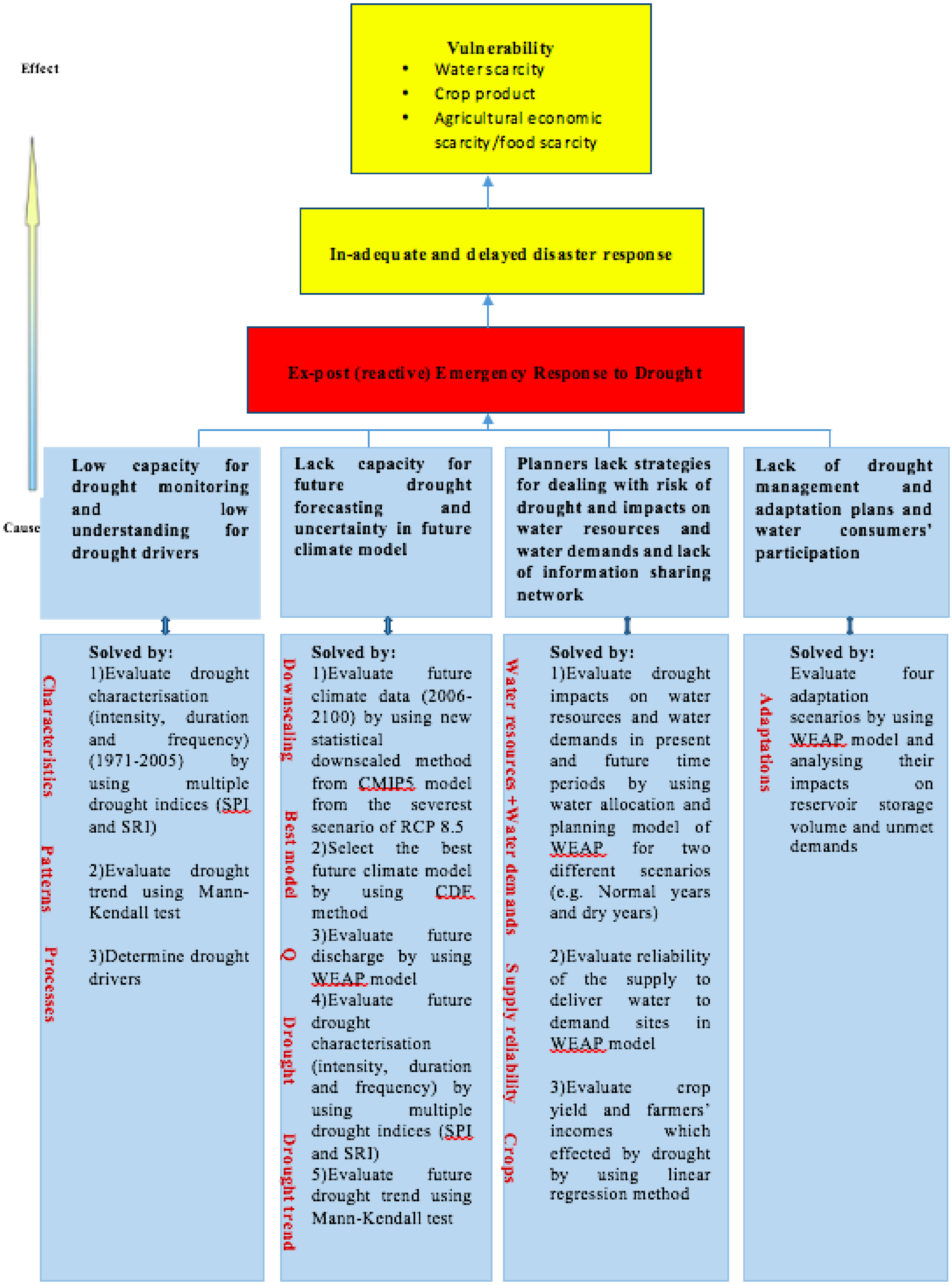


Figure 8.1: Conceptual model for the key elements of the thesis

8.2 General Summary

The incentive for this study originated from the FAO, which revealed information regarding climate, drought, and human impacts from developing countries (FAO, 2012b, FAO, 2011, FAO, 2012c). The report also emphasizes the need to carry out assessment studies on the potential impact of climate change on drought characteristics. The current study has addressed this gap in information for the arid developing country of Iran. The specific research gaps which link to the research objectives are identified below:

- Due to the complex nature and widespread impacts of drought there is not sufficient research for characterizing drought conditions and impacts; multiple drought related variations and indices are required to capture different aspects of complicated drought conditions(Mishra and Singh, 2011). So in this thesis to address this issue, the objectives of characterization of meteorological and hydrological drought using different drought indicators and selecting the criteria for drought identification have been achieved. Measurement of the severity, duration, and frequency of the drought and consideration of causes of historical droughts including large-scale climate, basin climate and some examples of human activities which influence water scarcity and drought in the basin have been obtained.
- More research and information is needed regarding drought impacts on surface and groundwater resources; and the significant long-term impacts of drought during different months on water demands. However, the lack of integrating socio-economic factors with the hydrometeorology of droughts is one major limitation of previous work which is analysed in this thesis. To address this issue the objective of evaluation and calibration of the hydrological model have been established. Application of the models to obtain the impacts of droughts on water supply and the water users and also human impact on flow reductions during the drought years has

been achieved. Also assessment of the socio-economic impacts of drought events on agriculture in the basin have been distinguished. Results will be used as input values for the integrated water management model to test the ability of the existing drought management framework to manage severe droughts.

- The other important gap is in considering the uncertainty introduced by the climate change models and by the chosen process of downscaling. Projecting the potential impact of future climate change on drought characteristics, water resources and water demands is essential, especially for regions where the projected climate change impacts and human effects on drought risks are both large. There is insufficient research to measure mitigation of the future drought impacts by adaptation scenarios. So to address this issue the objective of examination of the main factors of future climate change variables and comparison with historical data at the basin scale was considered. Assessment of the contribution of human withdrawals of water versus climate impacts on the future stream flow (runoff) to quantify anthropogenic influence is provided. Also determination of the impact of future climate change on drought severity, duration, and frequency using the Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI) at the basin scale without adaptation scenarios is addressed. Furthermore, application of future alternative management decisions adjusted to the situations and requirements derived from the outcomes of the application of the integrated water management models and further estimation of the usefulness of such measures is provided.

8.2.1 Research gaps identified and addressed

Chapter 2 addresses the first objective of this thesis which is characterization of the water organization units; recognizing physical and management features necessary for incorporated water planning adapted to the specific conditions of the unit. The chapter provided a substantial review of drought management, hydrological models, water planning models, climate change models and adaptation methods by drawing existing information together about the relationship between climate, drought management and anthropogenic impacts and water availability. The review demonstrated the interdisciplinary nature of this study by discussing literature across a range of subjects, such as integrated management, meteorology, hydrology, statistics, and social sciences. The major gaps identified and addressed are:

1) There is little research on the drought characteristics and drought management in arid developing countries, and none from the important river basin of Zayandeh Rud. Apart from (Raziei et al., 2009) who briefly reported drought risk, this study to the best of knowledge is the first of its kind that provides information on the relationship between climate, drought characteristics, water availability and water demands. This thesis developed a methodological approach for predicting droughts based on climate information and human impacts by mainly using statistical analysis to do drought characterization and including the effects of other non-climatic factors on creating drought events.
2) There is a requirement for further quantitative studies on drought characteristics and water resource planning that consider the additional effect of socioeconomic factors. So in this thesis multi drought indices are used to examine intensity, duration, frequency and spatial-temporal characterization of drought. Also to analyse the impact of drought on socio-economic factors, the number of farmers affected by drought, crop production and agricultural income lost during normal and dry years is evaluated.
3) The study adopted a multi disciplinary systematic approach (include drought characteristics estimation, water allocation model with analysis socio-economic factors and climate change model) to reducing the level of uncertainties in both

climate projection and drought impacts studies. The uncertainties were reduced by: (a) using a climatic-hydrologic time series (1971-2005) collected from the related institutions and government departements in the region; (b) accounting for the additional effects of the other non-climatic factors including population growth, exceeding water demands and high water abstraction, in the drought characteristics; (c) providing, calibrating and validating a water allocation model to analyse impacts of drought on water resources, water demands and investigate the socio-economic impacts of drough; (d) adopting the best model from a multi- model approach to drought projection by using an ensemble of 38 simulations from the most recent and improved GCMs that participated in the CMIP5 project; (e) statistically downscaling the simulations to the selected meteorological stations.

4) Projecting the potential impact of climate change on drought characteristics and providing essential adaptation scenarios. This research is the first, to evaluate the potential impact of climate change on drought characterization, water resources, water demands and crop yield using the GCM simulations with a new statistical downscale method from the CMIP5 project and to develop some adaptation scenarios.

From the above explanation, the new findings in this thesis provide integrated strategies that combine the modelling of agricultural technologies and agricultural management practices for drought management including: drought-tolerant crops, improved irrigation efficiency, decreasing crop area, climate change projection, and agricultural market information (i.e. crop yield and farmer ‘s income) that has enhanced drought risk management.

Increasing water scarcity problem for historical and future time period

Investigation

Objective1 -Chapter 2:
Identify research gaps; 1) little research on the drought characteristics and drought management in arid developing countries, especially in central of Asia-Iran which includes both climatic and non-climatic factors. 2) There is a requirement for further quantitative studies on drought characteristics and water resource planning that take into account the additional effect of socioeconomic factors, to improve the understanding of the drought management and adaptation plans. 3) Projecting the potential impact of future climate change on drought characteristics and provide adaptation scenarios are essential, especially for regions where the projected climate change impacts and human effects on drought risks are both large.

Select the methods, data analysis

Results

Objective 2-Chapter 3and 4: In chapter 4, the analysis of SPI-12 and SRI-12 represented that the frequency of drought occurrence deceased with increasing its duration. Meteorological drought impacts (represented by SPI) are expanded in hydrological drought impacts (represented by SRI) because of the increased temperature and decreased precipitation the nonlinear hydrological response to precipitation and temperature change quickly. The new finding and new results in this chapter is regional climatic factors are not only reason for drought. However additional factors can effect on drought risks for example the ENSO phenomenon significantly alters precipitation patterns across central Iran The construction of reservoirs with no sufficient surface water control or no measure of storage and convenience regulation in dry condition, lead more water demand that increased risk of hydrological drought.
Increasing demands and consumes more water for domestic, industrial and especially for agriculture through a higher evapotranspiration losses lead to streamflow drought. Also, the method of irrigation for example flooding the land for rice that is also the crop with high water use causes the duration of hydrological drought is longer compared to meteorological drought in the basin.

Objective 3-Chapter 5: Chapter 5 found that the differences between pure naturalized flow and naturalized flow with human effects increased almost linearly in time, which shows a more-or-less constant decrease of discharge due to exceed water abstraction. The measures also indicate that human influences in the most of the sub-catchments was on average two or three times as large as a natural influence, in deficit of the discharge. Because of the impacts of drought, the reliability of the supply to deliver water to demand sites decreased (2-15%). In addition, unmet demands during dry years are estimated 1.38 times more than unmet demands during normal years. Furthermore, crop production and agricultural incomes during normal years are 1.16 times more than dry years.

Objective 4 and 5-Chapter 6 and 7: Chapter 6 found that:1) future stream flows will decrease. Furthermore, the magnitude of future peak of maximum monthly stream flow (2006-2100) decreases by 27% compared with historical one (1971-2005). The climate model predicts that the basin does not have enough ability to release a large water volume. This means in comparison with historical stream flow, the mean of stream flow will decrease by 41% during the year of 2006-2100. 2) The current storage infrastructure will not be able to cover water demands sufficiently in the basin. The results show the reservoirs having serious drawdowns between years (2007-2025) and (2045-2067) and (2077-2099) which indicating a potential of the severest dry period. The water will deliver to the major domestic and industrial demand sites adequately up to the year 2100. However, irrigation demands experience shortage during the dry season in the range of 25 to 752 MCM. It will effect on crop yields and farmer’s income significantly. Chapter 7 found that with the new water management strategies and with four adaptation scenarios, future unmet demands can reduce between 2 and 15%.

New findings

1)Developing statistical analysis of both meteorological and hydrological variability in order to estimate the probability of drought intensity, duration and frequency could help to estimate drought characterisation and drought propagation more accurately. 2) Using water allocation model of WEAP, which includes a more detailed of water supplies and water demands, could provide analysis of natural flow and compare with natural flow with human impacts for normal and dry conditions. 3)Developing new climate model outputs by new statistical downscaling method and using CDF method to select the best future climate model could monitor and predict future drought characterisation better with less uncertainties.

Application

Figure 8.2: Summary of the research processes, which includes summary of the main results and new findings

8.2.2 Study area: selection and importance

The Zayandeh Rud River basin was chosen as the study site for this research as it is vulnerable to climate change due to its geographic location and associated meteorological and hydrological conditions and socioeconomic characteristics, (Newson, 2008). In particular, the region is characterized by indiscrimate water abstractions for anthropogenic uses and poor drought management thereby needing urgent attention. To analyze the drought characterization and impacts, the Zayandeh Rud River basin is suitable because of: (a) existence of at least one meteorological and hydrological station for each sub-catchment (b) existence of long-term measurement records at the stations.

8.2.3 Characteristics of meteorological and hydrological drought

Chapter 4 address the second objective of this thesis by applying a set of indicators based on precipitation and streamflow quantities. The values support the effective identification of drought intensities, periods and frequencies. Evaluating and monitoring drought characterization can help to make adaptation management that decreases the impacts of drought on the system. Chapter 4 found that during the study period (1971-2005), at least one extreme drought was detected at the stations, and the most severe meteorological droughts occurred in the winter and spring months. However, the most severe hydrological droughts occurred in the summer and autumn months The longest duration of the severest meteorological droughts in the year of 2000 was 2 to 8 months, and the longest hydrological droughts were 7 to 12 months. The analysis of SPI-12 and SRI-12 represented that the frequency of drought occurrence deceased with increasing its duration. Meteorological drought impacts (represented by SPI) are expanded in hydrological drought impacts (represented by SRI) because of the increased temperature and decreased precipitation the nonlinear hydrological response to precipitation and temperature change quickly. The new finding and new results in this chapter are in addition to regional climatic factors, which affect drought risks; for example the ENSO phenomenon significantly alters precipitation patterns across the Zayandeh Rud basin and is one of the main drivers of droughts (see section 4.3.7.1). The construction of reservoirs with insufficient surface water control or no measure of storage leads to increased risk of hydrological drought.

Increasing demands and consummation of more water for domestic, industrial and agricultural needs through higher evapotranspiration losses lead to streamflow drought. In general, consuming more from surface water leads to lower flows during the dry season, which means that droughts in streamflow increases.

8.2.4 Modelling the present day hydrology and investigating drought impacts on water resources and water demands

The present land use, water abstractions, and water infrastructure were added on the naturalized hydrology in the WEAP model to simulate the basin's water allocation. Chapter 5 addresses the third objective of this study by applying the output results of the WEAP model. The model simulation was calibrated against observed stream flow data (for stations located near the outlet of the given zone) to quantify the effect of climate and human influences on anomalies in the time series of the stream flow.

It was found that the differences between pure naturalized flow and the flow with human effects increased almost linearly in time, which shows a more-or-less constant decrease of discharge due to excess water abstraction. The measures also indicate that human influences in most of the sub-catchments were two or three times as large as a natural influence, in deficit of the discharge (see Figure 6.14 and 6.15 and Table 6.2 in appendix) .

The model performance was lower compared to the calibration stage with the Nash Sutcliff value (E values). A similar result for R^2 was also obtained (see Chapter 5). The model overestimates most of the peaks except for the extremes.

In summary, the model performance is good, and WEAP offers a simplified illustration of the complicated mechanisms of basin hydrology. The purpose of modelling in his thesis is to provide a framework to measure the influences of climate and humans on stream flow under normal, dry condition scenarios, and investigate the impacts of drought on water demands. For the present day conditions, the system has some uncertainties and assumptions which should be provided because defining them was beyond the reach of this study. Some of the main assumptions and uncertainties are explained as follows:

a) Most of the parameters that were used for the aquifer characteristics and also the values of the runoff/infiltration ratio are based on assumptions and may have been overestimated, because there is not enough valid data.

b) Reservoir operating rules could not be acquired in time; thus, the reservoirs have been modelled without operating rules. This may have contributed to the poor results of most dams.

Advantages and disadvantages of WEAP

WEAP suggestions an 'under one roof' approach to simulating a river basin. This indicates that the model can simulate the hydrology, water quality, water requirements and economics of applying water infrastructure increases at a single go. So, the model makes a holistic view of the whole working of a river basin. This section indicates the pros and cons of WEAP.

Some of the strengths of WEAP:

1) An IWRM integrated water resources management semi-distributed model WEAP (Water Evaluation And Planning) was utilized because it is a useful tool to simulate hydrological responses to human water abstractions and climatic changes. A semi-distributed model is

selected because in regards to the available data for this thesis, the model needs less data in comparison with fully distributed models.

The WEAP model is a kind of semi-distributed model, which considers a catchment as a series of lumped models. Therefore, the model in this research simulates the average hydrological behaviour through small homogeneous units for the entire Zayandeh Rud basin.

2) The WEAP was a powerful tool for gathering all the information of water balances and water allocation among water users. Also for this thesis it provided a model which includes all values of rainfall- runoff, infiltration, groundwater storage, evapotranspiration, crop necessities, industry and domestic demands, water infrastructures; such as dams and inter-basin transfers, population trend and farmers' income trend. The WEAP dynamically connected to spreadsheets and also provided a strong description containing graphs, tables, and maps.

3) This thesis tried to show the reflection of the drought on water resources and water demands and compare it with normal conditions. Therefore, WEAP created two scenarios for dry and normal years, which contain population trend, crop yield and farmers' income trend.

4) This work tried to display existing data sets of hydrology more precisely by using GIS; so the WEAP model could link to GIS data.

5) Even with some unfixed parameters (e.g. effective precipitation, runoff/infiltration ratio, hydraulic conductivity and crop coefficient) in this thesis, the WEAP model could do a simulation based on assumption values.

However, there are some disadvantages of WEAP:

1) The main disadvantage of WEAP is the absence of any uncertainty analysis routine. Also another disadvantage of WEAP is the absence of an inherent automated calibration function. There was no optimization routine for calibration processing and it was done manually by trial and error in this thesis.

2) For this study, the model set up of 34-years' simulation of the basin processes for the historical period and 94-years' simulation for a future period took significant time (2 hours to completely run a model for each 34 years) on an average computer. Thus, a faster computer would be needed for a comprehensive analysis.
3) In the hydrology model of this thesis, some important parameters such as soil water depth which affect stream flow values could not be used in calculations of linear programming of the WEAP.

8.2.5 Projecting the impact of climate change on drought characterization, water resources and water demands

Chapters 6 and 7 address the fourth and fifth objectives of this thesis by applying the future climate change model and validated water allocation model to assess the potential impact of climate change on (1) drought characterization (2) water availability and (3) unmet demands in the Zayandeh Rud river basin. A group of variables from the the GCM climate simulation that participated in the CMIP5 was statistically downscaled for this research study and these were input as initial variables in the water allocation model. Due to future forecasts of higher temperatures and less precipitation, the results showed increases in both meteorological and hydrological droughts intensity in the future. Results show that these changes are largest and most statistically significant during the winter and spring seasons for meteorological drought and during the summer and autumn seasons for hydrological drought which cause increasing in unmet water demands significantly. In addition, the effect of snowfall on drought is not considered in this study, because there was no data available for snowfall. However, according to the literature review from Regional Esfahan Water Authority report, during the year of 1971-2005 the snowfall has decreased significantly (with decreased rainfall as well) that caused reduction of discharge and water availability in the basin.

Also the climatic data from GCMs with the severest scenario are used in the WEAP model to investigate future discharge, future drought and effect of climate alteration on water availability in the Zayandeh Rud river basin.

The results for the future time period reveal:

a) Future stream flows will decrease. Furthermore, the magnitude of the peak of maximum monthly stream flow (2006-2075) decreases by 27% compared with historical peak (1971-2005). The climate model predicts that the basin does not have enough ability to release a large water volume. This means in comparison with historical stream flow, the mean of the stream flow will decrease by 41% during 2006-2075.
b) The current storage infrastructure will not be able to cover water demands sufficiently in the basin. The results show the reservoirs having serious drawdowns in both near and far future period; which indicate a potential of the severest dry period.
c) The water will deliver to the major domestic and industrial demand sites adequately up to the year 2100. However, irrigation demands experience shortages during the dry season in the range of 25 to 752 MCM. It will affect crop yields and farmers' incomes significantly. The significant areas having deficits lie within sub-catchment 4202.

8.3 Synthesis

A downscaled climate change model with the scenario of RCP 8.5 was provided with monthly projected changes in temperature and precipitation for the period of 2006 to 2100. Based on the results from the climate scenario, a warmer climate is predicted for the region with a projected change of temperature between 2 and 7°C for the autumn and summer seasons. Based on the climate scenario, the precipitation is predicted to increase only for the months of July, August and September between 10% and 20% and to decrease for the other months between -30 and -70%. These alterations were applied to calculate future stream flow using the WEAP model. The WEAP model was calibrated to an existing historical data set (for 1971-2005) for the Zayandeh Rud river basin and then used to explore the impact of future drought and climate change on the stream flows and water demands of the basin. Demands of urban and agricultural areas were projected to grow to the year 2100. For measuring the climate alteration effect on the watershed, the simulation model presumes that some of the physical catchment characterization like geography, soil and land cover will not alter for the projected period of examination and that the rainfall-runoff processes will remain constant. Also, the study hypothesized that the agricultural area and the kind of crops assigned in that area would not alter for the future time period. These are only hypotheses; nevertheless, they allow us to investigate and focus on the effects of climate alteration on hydrology. The outcomes of these projections reveal that without adaptation scenarios the anticipated demands will not completely be met, because of the rise in water requirement and decline in precipitation, and increased temperature during the long term trigger the system to be incapable of meeting the demands. The four adjustment scenarios were assessed to either increase water resources or decrease the demand for water from the agricultural zone. The scenarios include making new water resources, increasing irrigation efficiency, decreasing crop area and changing crop patterns. It should be noticed that for each of the adjustment scenarios, the outcomes have been revealed for drought periods (the severest scenario). The outcomes of the adaptation scenarios indicated that all of them have moderately long-term effects. The influences of all scenarios, regarding avoiding unmet demands, were projected to 2100. Among the four adjustment scenarios the improved irrigation efficiency and reduced crop area scenario had the smallest effect regarding the decrease of shortages.

For analysing the impacts of adaptation scenarios, also changing the volume of reservoir storage is applied to alleviate the variability of inflows; it can control a portion of the variability. In addition, a comparison of the volume of reservoir storage, water availability and its ability to cover unmet demands for each sub-catchment, was done between the four adaptation scenarios.

In this study, reservoir operational rules were assumed to be constant. On the other hand, the reservoir operational rules can alter over time. Regarding the requirement of suitable reservoir operational rules for water supply, obtaining standard operational policy and the action of managers and their ability to deal with reservoir operational problems during drought periods, they all have very important roles which are missing in the present management. Altering operational rules may influence the dispersal during the year but should not influence negatively on water sustainability in each year. Thus, the alterations in the reservoir operational rules would likely affect the results less than possible alterations in the watershed. If the watershed makes further stream flow, hence, the reservoir would have greater water to release, and the volume of unmet demands would decrease and might be postponed further in the future. If the catchment makes low stream flow the volume of unmet demands would rise. So the outcomes from this study represented that with rising demand and decreased stream flow the volume of unmet demands will grow. However, the novel adaptation scenario with simulating new water resources (e.g. transfer water from neighbour catchment and construct two storage dams) tried to compensate this stress.

Although the Zayandeh Rud river basin is located in a developing country, the knowledge achieved through this study can be applied to develop water management plans for river basins of the developed world where similar or different socio-economic conditions may occur. Firstly because this study developed a comprehensive interdisciplinary framework for hazard management, water resource, environment and social factors that used an integrated system approach to the development of solutions for water supply management and hazard adaptation. Secondly because this study answered the questions of: 1) what perspectives are not being considered significantly in water resource management during extreme events in basin scale. To answer this question this study monitored and analysed characterization of two kinds of drought (in Chapter 4) which can be useful for water managers to know early warning and persistent of drought. 2) What climate and non climatic factors (such as human activities) effects on drought characterization. To answer this question this study analysed some experimental data such as effect of: increased evapotranspiration, land use, crop pattern change, new water resource development, increased population on drought characterization (in Chapter 4). 3) What are the major effects of drought on both physical and social infrastructures. To answer this question this study examines the operation of related institutions of water resource management by investigating unmet demands, losses of crop productions and farmer's income during normal and dry years (in Chapter 5). 4) What are provisions of future climate change and impact on water resources. To answer this question this study used simulations from an ensemble of statistically downscaled CMIP5 model. 5) What are the localize adaptation plans with regards to uncertainties associated with inter annual and longer climate variations as well as altering social values pose risk for managing water system. To answer this question this study present information for decisions including develop alternative water management strategies and compare and evaluate them by applying multi- criteria analysis.

For better management of water resources in terms of institutional context, this study suggests improvement in the commitment of governments to implementing and developing drought characterization monitoring, analysing drought drivers and impacts on water resources for long term climate change. Also, this study suggests improving coordination between Ministry of Energy, Ministry of Agriculture and Regional Water Authority who involve in water resource and water using management. Furthermore, it would be useful if governments allow a group of researchers to participate in decision making of water resource management during extreme events.

8.4 Recommendations for future research

This study has also showed some potential research options that would be interesting to investigate in detail:

- To develop the outputs of drought impacts on water resources and water demands, collection of more field data to represent the soils and land cover change is necessary. Therefore, a simulation model of soil erosion, which affects hydrological drought can be suggested.
- To improve the results of drought impacts on water resources and water demands and also the use of the water allocation model capabilities, development of the automatic calibration of the model is proposed. It must be used through applying third party algorithms such as the Parameter ESTimation (PEST) tool (Doherty, 2004) or writing code to be applied in WEAP. This can develop the calibration progression through supporting the modeller in the creation of more knowledgeable judgments on model factors and their optimum standards.
- Also, with providing complete and sufficient groundwater data, the ground water element can be integrated into the model to simulate the hydrogeology. This can provide the full image of water supplies in the Zayandeh Rud river basin. The groundwater element can be set up by applying MODFLOW and connecting to WEAP. However, there are some limitations; because MODFLOW is so detailed, preparation of data in suitable spatial and temporal scale and running an initial MODFLOW model may not possible for all river basins. Also, for linking WEAP (2D model) to MODFLOW (3D model), creating a GIS shape file to connect the WEAP elements to the MODFLOW cells is necessary. However maybe flow cannot discharge at a sufficiently large rate to capture all of the flow entering the cell. So,

some of the flow leaves the cell across one or more of the cell faces and understanding water discharges to the sink or passes through the cell is not easy.

- The costing unit can be applied to determine the expense of new infrastructure, functioning costs and consequential profits from the water infrastructure. This is important especially in developing country like Iran, with low economic levels, water managers prefer that conservation of water leads only to low expense.
- Inclusion of Biological Oxygen Demand (BOD) values in the WEAP model could help to understand the impacts of leaching of nitrates from agricultural soil into freshwaters and help design more comprehensive integrated water management strategies. So, it would be helpful to add another model like BASINS for the estimation of water quality during the drought occurrences. The combination of such evaluations in the integrated water organization model might be useful to describe ideal fertilizer inputs for crops as per the estimation of drought detection indicators and capture possible socio-economic issues from unmet demands from measurable and qualitative perspectives.
- The most recently updated version of GCM simulations from the CMIP5 project has been used in this study. However, using the outputs from use of CMIP5 models to the higher resolution of Regional Climate Model (RCM) data in future research studies would be more appropriate. as it can help to decrease uncertainties in climate models. RCM is advantageous in such cases as the model can provide high-resolution outputs, and allows for the illustration of small-scale progressions like soil characteristics. Generally, an RCM is very similar to a GCM however it covers a smaller spatial domain, at a higher resolution. The GCM provides the environmental conditions, normally for every 3 or 6 hours, at the boundaries of the RCM domain. RCMs provide both better topographical representations than GCMs and better local-

to regional- scale atmospheric dynamics that may, for example, develop the simulation of warm-season convective precipitation.

However, a regional climate model usually is fixed to one GCM and it will not be possible to estimate the differences of GCMs.

- In this study, the model of integrated water management allows for the examination of scenarios expressed by other factors such as more policy adaptation that can involve land use alterations or differences in entire water demands originated from changes in other aspects.

The recommended organization for the study could be helpful to create an improved model of sustainable water management (specially during drought periods) which can cover the water demands with less impacts on water supplies.

8.5 Research application

Drought episodes are multidimensional progressions that influence many aspects of environmental, social and economic life concurrently. Most previous research only focused on one feature of drought and only analysed climatic factors of drought; non-climatic factors of drought like human influences (such as developing infrastructures and excess water abstractions) are neglected. Therefore, the novel approach of this thesis is providing complex analysis proprieties that combine a wide range of possible important aspects. This study is an effort to overcome previous restrictions of drought examination through integrating climatic, hydrological, anthropogenic, agricultural and effective characteristics. Therefore, it will be helpful as a developed methodological framework for increasing drought risk management. The main science finding is drought conditions may be created by both climatic and non-climatic dimensions, which by the observation-modelling framework in this thesis is distinguished (see section 4.3.7.3 which shows human activities coincide with flow defecit and may cause hydrologicl drought) .

The outcomes from this study are not planned only for an academic aim; it is intended that they will provide the basis for drought characterization and forecasting services using climate and socioeconomic information in central Iran. The improved statistical analysis and validating models have the capacity and robustness to anticipate future droughts and their impacts on water resources and water demands.

The results from future projection of drought characterization, future water allocation models under dry conditions can give water managers a tool to differentiate between natural and human effects and could help them design water managements strategies. However, in future studies data related to water quality related parameters (e.g. BOD), contemporary cropping patterns, and ground water flows could help to make projection estimations more robust. Furthermore, fine tuning the existing models' ability to predict different time scales, and also by examining appropriate ways of using the prediction product could strengthen the water management policies and plans. This work could be very useful for planners and decision makers dealing with and overseeing water resources' management and crop production for future years. The results can contribute to the understanding of regional scientific communities of climate change's impacts and human influences on water resources. The outcomes could be used to support future water resources' planning and management in Iran and other catchments with same climatic conditions.

It is proposed that the results of this thesis is communicated to the relevant institutions in Iran, such as the Ministry of Energy, Ministry of Agriculture, Iran Water Resources, Esfahan Regional Water Authority and Esfahan Environment Organization. This will provide inputs to operational water resources management strategies and plans. The outputs of the thesis can be used for evaluating and improving appropriate institutional structures to create a best practice guidance tool to manage this information locally, in coordination with the relevant institutions and agencies in the country. However, there are some challenges for agreement in drought management, which not only depend on improving scientific approaches but also related to the policies and political motivation and will. For example, differences and biases in water pricing for different regions and different water consumers can affect the amount of water uses and also affect the intensity of the hydrological drought. In order to access the necessary data and to share possible methods for drought management, this thesis has already provided a large network of institutions that are interested in drought monitoring, forecasting and evaluation of the risks and impacts of water resources and water demands such as the International Water Management Institute (IWMI); the National Centre for Atmospheric Research in the global scale and in the regional scale.

APPENDIX I: Application of the WEAP in the world, referred to in Chapter 2

International Projects:

- ✓ The first project in the Aral Sea region performed for the examination of water accounts and assessing water management strategies (Raskin et al., 1992).
- ✓ In the United States of America (U.S.A) for hydrological modeling (Amato et al., 2006), water consumption, water allocation (Yates et al., 2007)and influences of climate alteration on agriculture studies (Purkey et al., 2008)a WEAP model established. Also, the Hydrologic Engineering Center (HEC) of the U.S Army Corps of Engineers applied WEAP for planning studies of water resource in several regions in the Unites States of America.
- ✓ In the Mideast to perform another water improvement and allocation scenarios involving both Palestinian and Israeli cooperation WEAP model used. Also, in Litani Basin in Lebanon for improving and evaluating water quality management strategies to decrease the discharge of untreated wastewater into the Upper of the basin, (Assaf and Saadeh, 2008) used the WEAP model.
- ✓ In the Beijing - Hebei Eco-Region, WEAP model applied to make the foundation for attaining collaboration on water sharing problems between upstream and downstream stakeholders in 14 regions of Hebei Province. Also, the model combined with other models of solid waste to improve the Beijing Environmental Master Plan Application System for the Beijing Municipal Environmental Planning Bureau (HAO and WANG, 2012).
- ✓ In Kenya, (Alfarra, 2004), used WEAP for modeling water supply management in Lake Naivasha. Also for water allocation studies in the Tana Basin under the Green Water Credits Program, the model is applied(Hoff et al., 2007). To model the effects

of small reservoirs in an arid and semi-arid areas in Ghana, WEAP model is applied (Hagan, 2007).

- ✓ Also, (Arranz and McCartney, 2007) used WEAP to estimate the effects of three scenarios of water demand growing, in Olifants catchment in the south of Africa.

APPENDIX II (A): Information about meteorological and hydrological stations, referred to in Chapter 3

A) Meteorologica stations:

✓ Tipping Bucket Rain Gauge (TBRG)-Rainfall sensor:

A stainless steel tipping bucket rain gauge is applied for measurement of rainfall volume. The collector diameter is 20 cm and the resolution of the gauge is 0.5 mm. So, 15.7 cm3 (product of collector area and resolution) of rain water corresponds to 0.5 mm of rainfall. The large collector area assists avoid the loss of rainfall because of evaporation. The rain water go into the funnel inside the gauge and is directed to one of the two tipping bucket. Each bucket is calibrated to tip when 15.7 cm3 of rain water is collected in it. At any given time one bucket is always in collection mode. As the bucket tips it produces a 4 magnet to pass by a ruggedized mercury switch, momentarily (0.05 sec) closing the switch. The contact closure initiates event or count accumulation in the data logger. Once the rain is measured, the rain water is directed into drain tubes that let it to exit through the base of the gauge. The accuracy of the rain gauge is within 2% at 240 mm/h. Hourly rainfall and daily rainfall can measure.

✓ Air Temperature and Relative Humidity (AT/RH):

An Air Temperature/ Relative Humidity measurements are examined at a height of 2 m above ground level. The sensor is mounted in naturally ventilated radiation shield. The sensor uses THERMISTOR for air temperature measurement and HYGROMER sensor for humidity. A sample of one minute is taken for hourly Maximum and Minimum Temperature measurement. A 5 volts excitation voltage is needed for the sensor and is continuously powered. The hourly air temperature and relative humidity along with hourly maximum and minimum temperature are transmitted from field station.

B) Hydrological stations

For each hydrological station, in place of the direct measurement of streamflow discharge, one or more surrogate measurements is used to make discharge values. A stage (the elevation of the water surface) measurement is applied as the surrogate. Furthermore, a variety of hydraulic structures / primary device are used to improve the reliability of using water level as a surrogate for flow (improving the accuracy of the rating table), including: weirs, flumes.

Also velocity sensors measure velocity at a particular location in the stream for each hydrological station in daily scale.

APPENDIX II (B): Information about modeling process and structure of WEAP , referred to in Chapter 3

MODELLING PROCESS OF WEAP:

WEAP21 is designed as a set of five various "views" onto the working Area: Schematic, Data, Results, Overview and Notes. These views are listed as graphical icons on the View Bar, located on the left of the screen. The Current Accounts denote the basic definition of the water system as it currently exists, and forms the foundation of all scenarios analysis. Scenarios are self-consistent story-lines of how a future system might evolve over time in a particular climate change, socio-economic setting and under a specific set of policy and technology conditions. The comparison of these alternative scenarios can provide a useful guide to development policy for water systems from local to regional scales (Vogel et al., 2007). The main screen of the WEAP system consists of the View Bar on the left of the screen and a main menu at the top providing access to the most important functions of the program. WEAP calculates a water quantity and pollution mass balance for every node and link in the system on a monthly time step. Water is dispatched to meet instream and consumptive requirements, subject to demand priorities, supply preferences, mass balance and other constraints.

The modeling of a watershed using the WEAP contains four steps (Levite et al., 2003): 1) Description of the study area and time frame. The setting up of the time frame includes the last year of scenario creation (last year of analysis) and the initial year of application. 2) Making of the Current Account which is more or less the existing water supplies condition of the study area. Under the current account available water resources and various existing demand nodes are specified. This is very important since it forms the basis of the whole modeling process. This can be used for calibration of the model to adapt it to the existing situation of the study area. 3) Making of scenarios based on future assumptions and expected increases in the various indicators. This forms the main or the heart of the WEAP model because this allows for potential water resources management processes to be approved from the results generated from running the model. The scenarios are used to address a lot of “what if situations”, like what if new reservoirs build, what if climate change happen, what if there is a population increase and etc. Scenarios creation can take into consideration factors that change with time. 4) Evaluation of the scenarios with regards to the availability of the water resources for the study area. Results generated from the creation of scenarios can help the water resources planner in decision making, which is the core of this study.

ALGORITHM STRUCTUReE:

WEAP uses a hierarchical structure to disaggregate water demand data. One can easily adapt this structure to the nature of the problem and data availability. The first level corresponds to the demand sites (sector demands for example, domestic, agriculture, municipal). One can create as many levels necessary to explicitly disaggregate demand. A demand site's (DS) is needed for water and it is calculated as the sum of the consumptions for all the demand site's bottom-level branches (Br). A bottom-level branch is one that has no branches below it (disaggregated from the sectoral demands). Annual Demand DS = (Total Activity Level Br x Water Use Rate Br). The total activity level for a bottom-level branch is the product of the activity levels in all branches from the bottom branch back up to the demand site branch (where Br is the bottom-level branch, Br' is the parent of Br, Br'' is the grandparent of Br, etc.). Total Activity Level Br = Activity Level Br x Activity Level Br' x Activity Level Br'' x...

Monthly demand: To specify the demand for each month, typically using the ReadFromFile function, or by entering direct in WEAP using the monthly time series wizard.

Monthly Supply Requirement: the supply requirement is the actual amount needed from the supply sources. The supply requirement takes the demand and adjusts it to account for internal reuse, demand side management strategies (DSMS) for reducing demand, and internal losses. Monthly Supply Requirement DS,m = (Monthly Demand DS,m x (1 – Reuse Rate DS) x (1 – DSM Savings DS))/ (1 – Loss Rate DS).

Inflows and Outflows of Water: this step computes water inflows to and outflows from every node and link in the system in monthly time steps. This includes calculating withdrawals from supply sources to meet demand. Hydrologic analysis can do through three different method: 1) the Food and Agriculture Organization (FAO)method 2) soil moisture method and 3) rainfall-runoff models. In this study with regards to data availability, the rainfall-runoff model is selected

CATCHMENT HYDROLOGY:

The Rainfall Runoff method determines evapotranspiration for irrigated (or rainfed) crops using crop coefficients. The remainder of rainfall not consumed by evapotranspiration is simulated as runoff to a river, or can be proportioned among runoff to a river and flow to groundwater via catchment links.

APPENDIX III: Figures referred to in Chapter 4

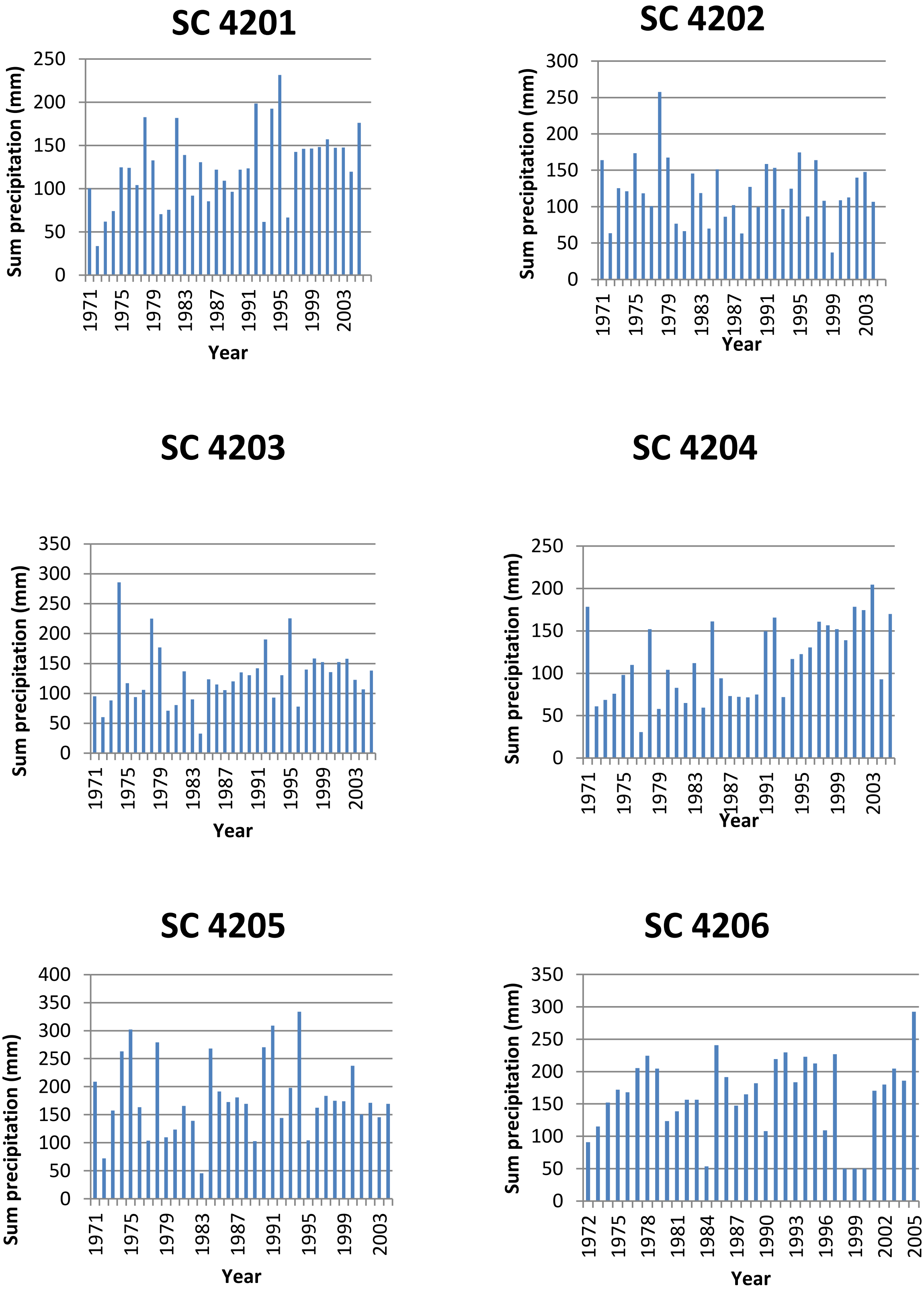
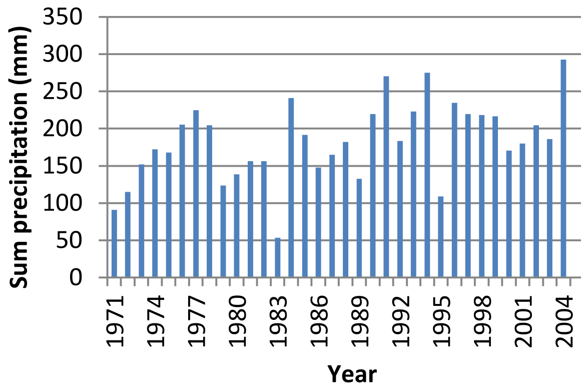
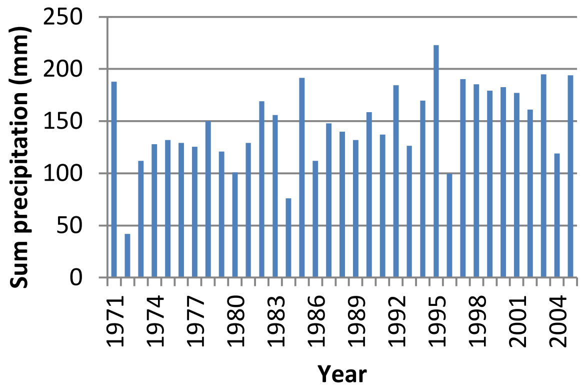


Figure 4.1: Time series of the sum annual rainfall series of the year 1971 to 2005 at the different sub-catchments of the Zayandeh rud basin

SC 4207



SC 4208



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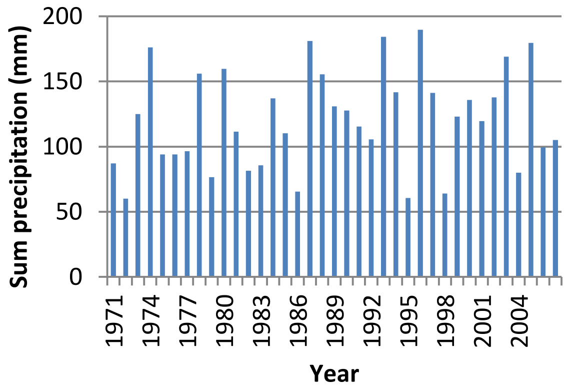
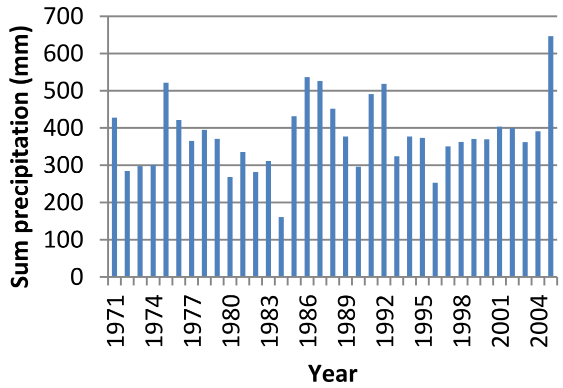


SC 4210



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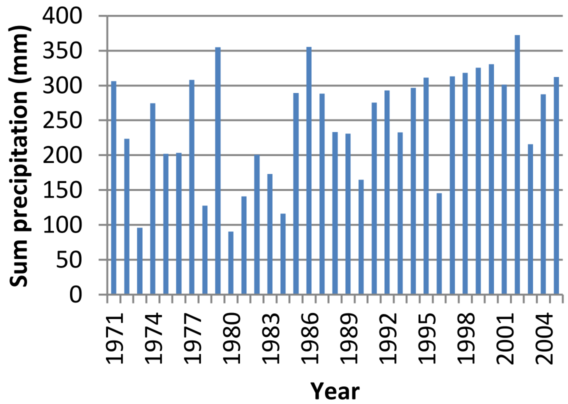


SC 4212

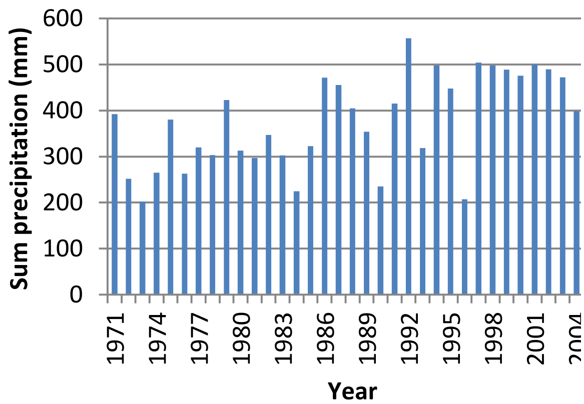
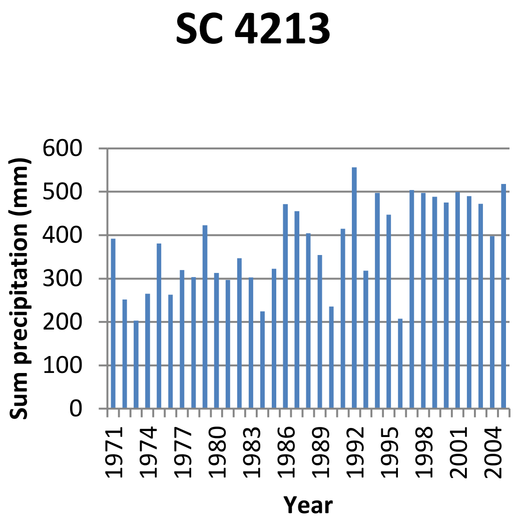
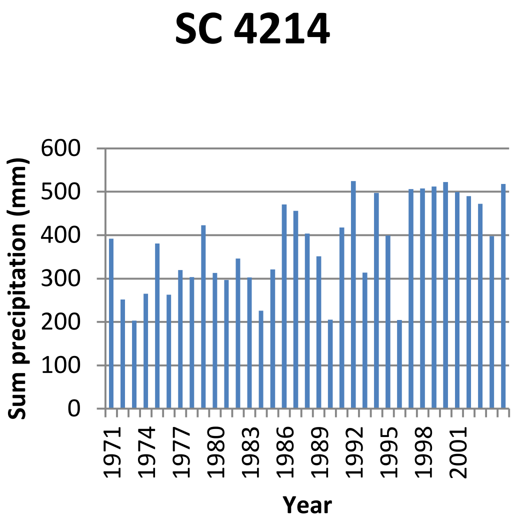
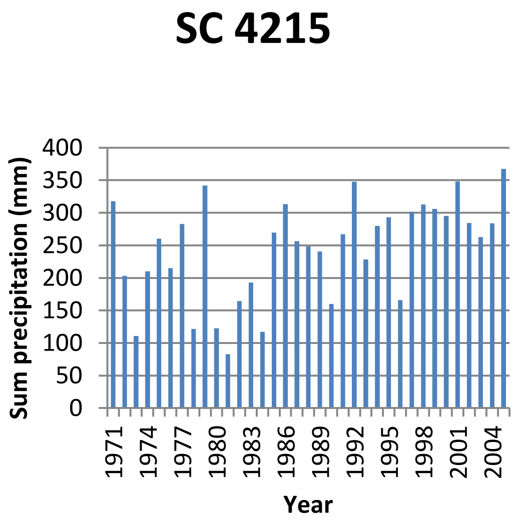
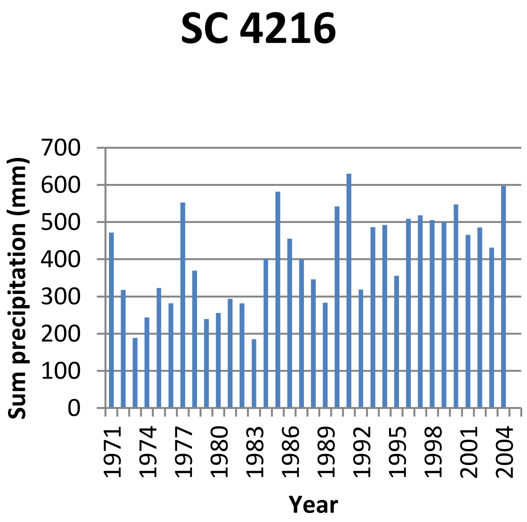


Figure 4.1: Countinued









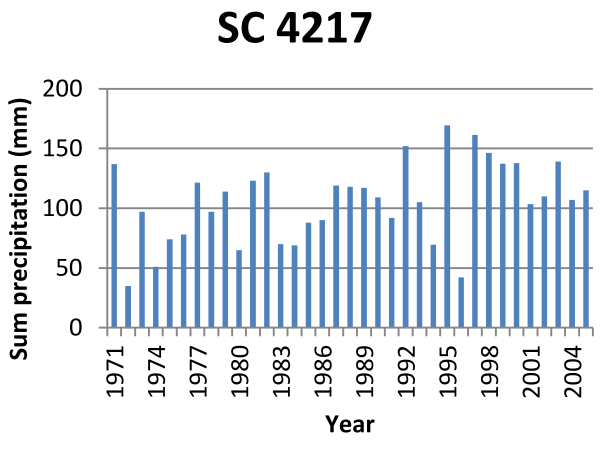


Figure 4.1: Countinued

APPENDIX IV: Figures referred to in Chapter 5

Explanation of the modelling the reservoirs and defult operating rules in WEAP

In Figure 5.1, the flood control storage (Sf) describes the zone that can hold water temporarily however should be released before the end of the time step. Therefore, storages above the flood control storage are dropped. The conservation storage (Sc) is the storage available for downstream requirements at full capacity. The buffer storage (Sb) is a storage that can be controlled to meet water requirements during storages. When reservoir storage falls within the buffer storage, water withdrawals are saved efficiently by the buffer coefficient (bc) which determines the fraction of storage available for release; the inactive storage (Si) is the dead stoage that can not be used.

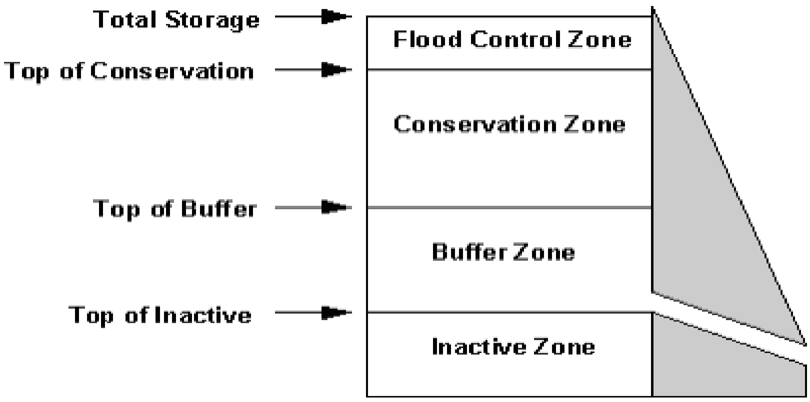


Figure 5.1: Reservoir storage zones applied to explain operating rules.

Equation for calculating evapotranspiration:

$$ET_0 = 1.6 * (10\, T_I / J)^C \qquad \text{(Equ 1)}$$

Where ET_0 is potential evapotranspiration (mm) and T_I monthly mean temperature (^{0}C) and J=a heat index which is a constant for a given location and is the sum of 12 monthly index values i, where i is a function of the monthly normal temperatures. C=an empirically determined exponent which is a function of J, a=6.75X 13-7.71 X 10-512 +1.79X10-2 13.0.49.

$$\mathbf{ET_{real} = ET_0 * Kc * Area} \qquad \textbf{(Equ 2)}$$

Where ET_{real} is real evapotranspiration and ET_0 is potential evapotranspiration (mm) and Kc is crop coefficient and area is area under cultivation.

Equation for calculating effective rainfall by SCS method:

$$\mathbf{S = \frac{25400}{CN} - 254} \qquad \textbf{(Equ 3)}$$

Where S is potential storage in soil (mm) and CN is curve number and can calculate as a function of soil type, land use and degree of saturation. So, effective rainfall can calculate by:

$$\mathbf{Q = \frac{(P-I)^2}{(P+S-I)}} \qquad \textbf{(Equ 4)}$$

Where Q is effective rainfall (mm) and P is accumulated depth of rainfall in specific time (mm) and I is initial abstraction in mm and S is potential storage in the soil (mm)

Equation for calculating irrigatin demand:

(Et x PF x SF x 0.62) / IE = Gallons of Water per day **(Equ 5)**

Values for the formula:

Et: Evapotranspiration for major crops. The value achieved from climate variable models.

PF: This is the plant factor. Different plants need different amounts of water; a value of 1.0 for lawn; for water loving shrubs 0.80; for average water use shrubs 0.5; for low water use shrubs 0.3. The range of 0.6-0.8 is applied for most of the region in the Zayandeh Rud basin.

SF: This is the area to be irrigated and area under cultivation.

0.62: A constant value used for conversion.

IE: Irrigation efficiency. Some irrigation water never gets used by the plant. This value compensates for that factor. In the Zayandeh Rud basin the average irrigation efficiency is 34% because of the continued use of traditional irrigation systems such as flooding. However very well designed sprinkler systems with little run-off can have efficiencies of 80% (use 0.80). Drip irrigation systems typically have efficiencies of 90% (use 0.90). Therefore,

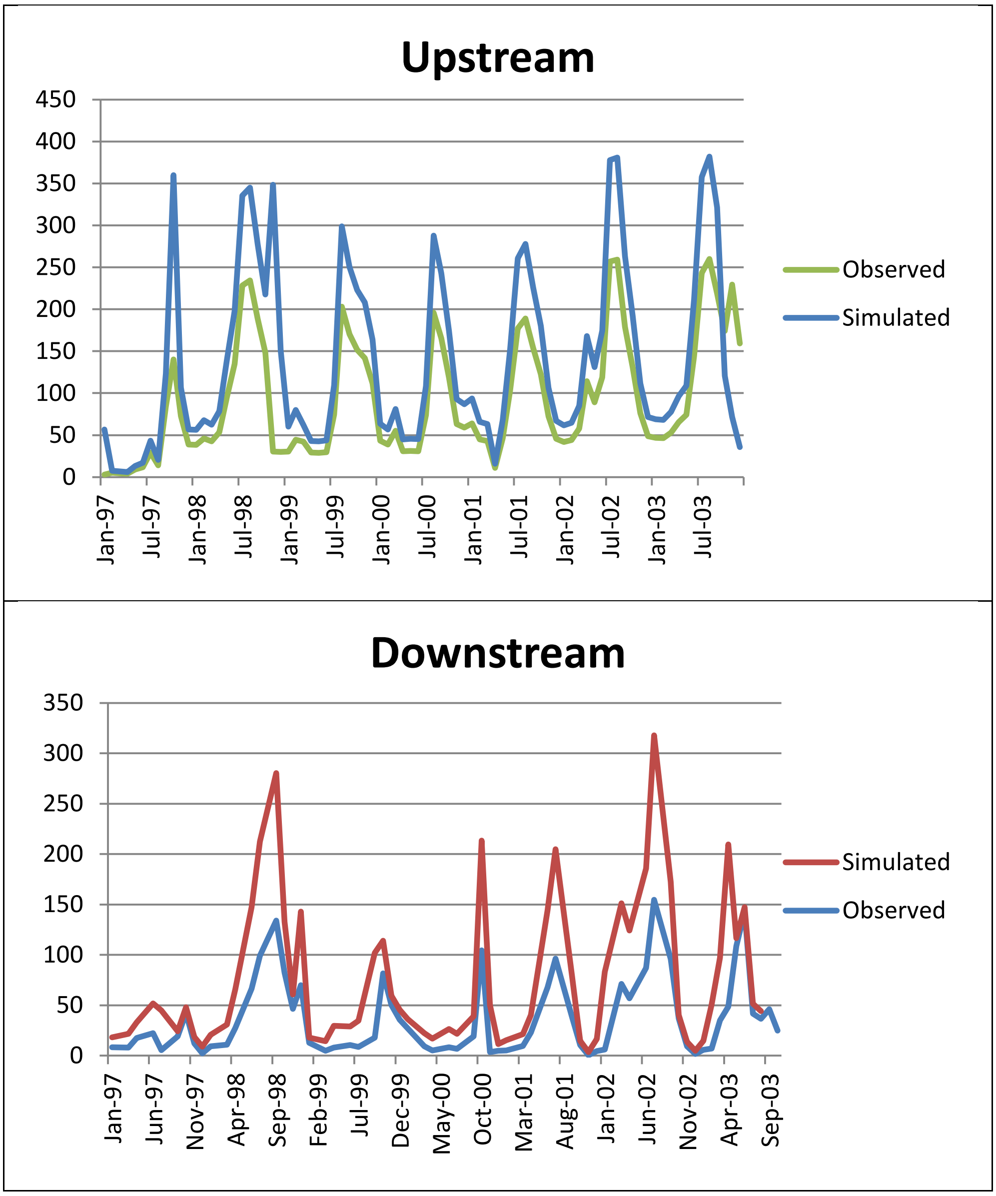


Figure 5.2: Simulation results using initial parameters

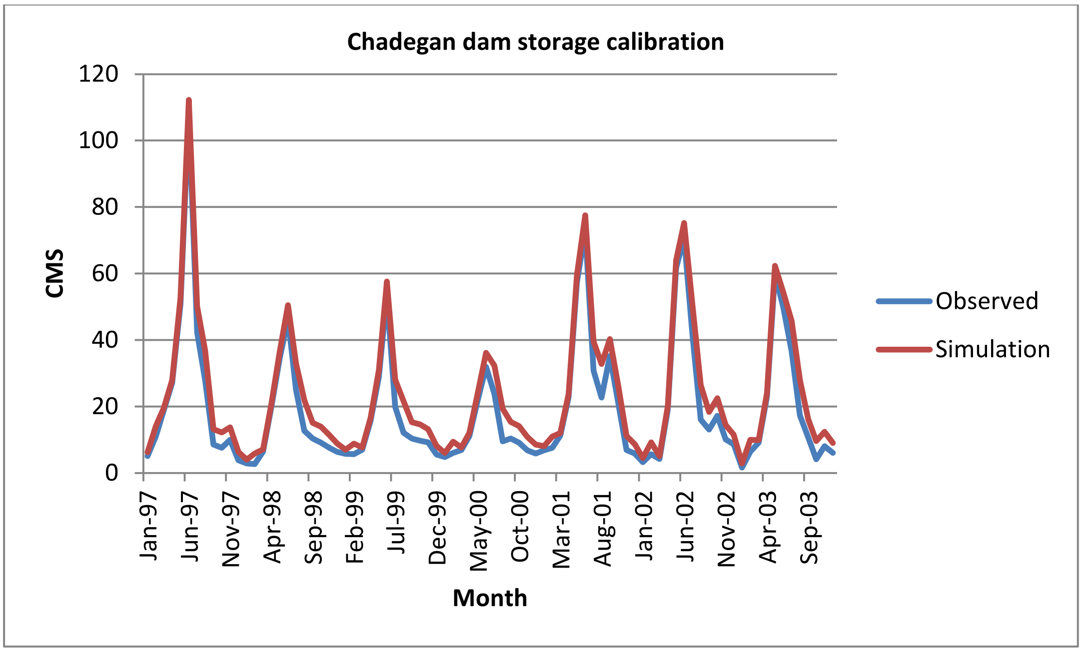


Figure 5.3: Simulation results for the Chadegan dam storage (the main and the most important dam in the Zayandeh Rud basin)

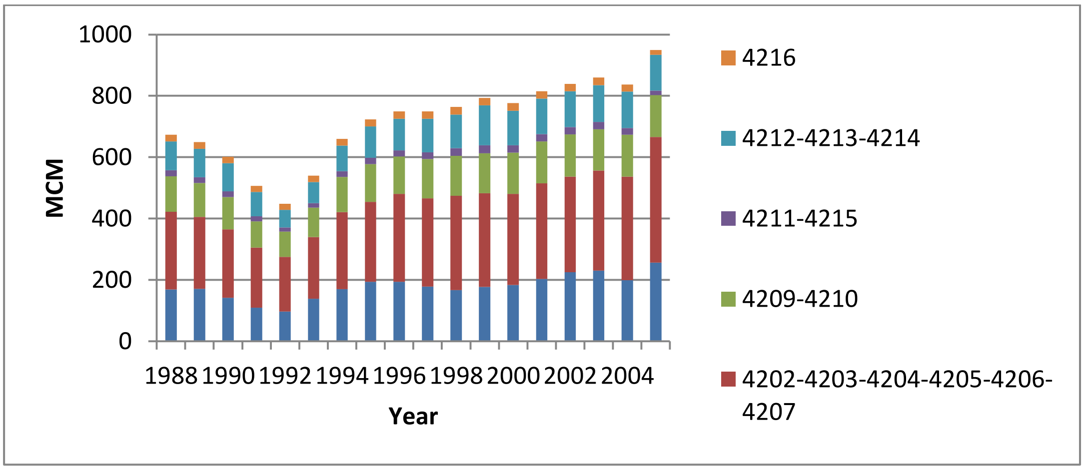


Figure 5.4: Sum water demands for agriculture, domestic and industry in different sub-catchments

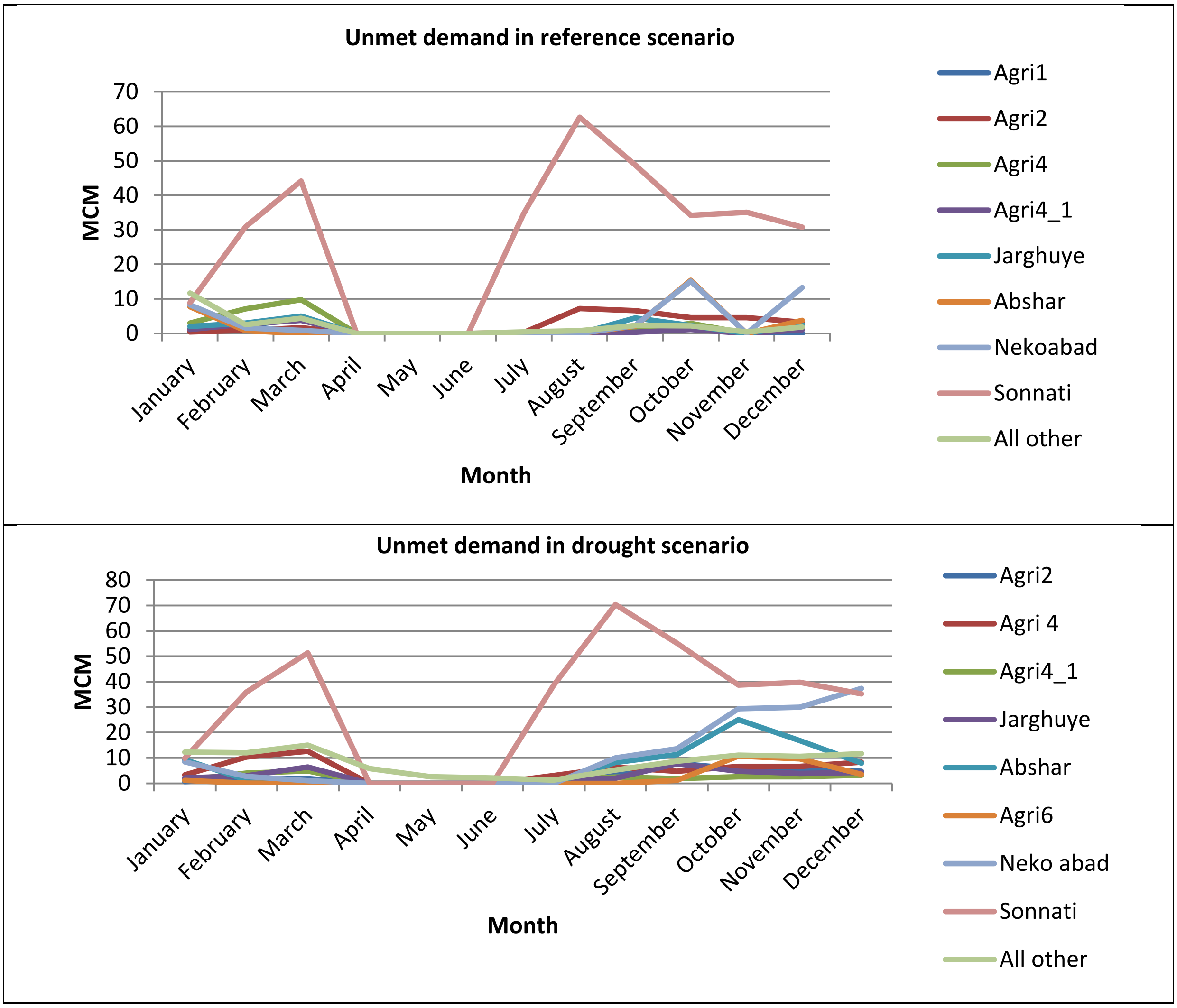


Figure 5.5: Unmet demands in each water user sectors in the Zayandeh Rud basin in the reference scenario

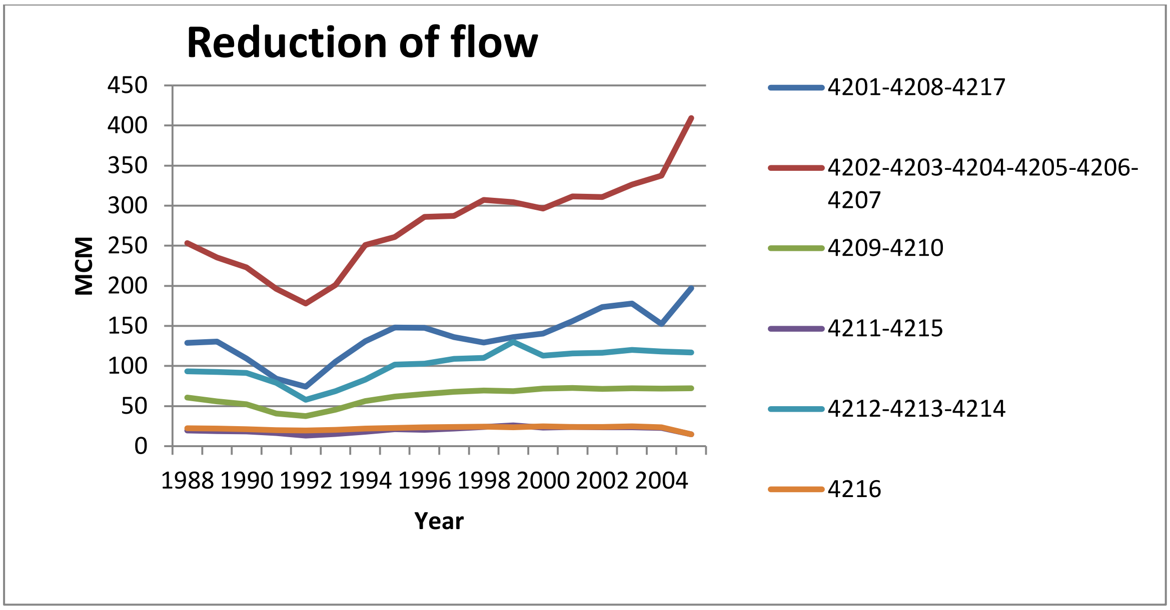


Figure 5.6: Reduction of flow with water abstraction for the sub-catchments during the year of 1988 to 2006. Especially during the last strong drought event in 1998 to 2000, the reduction increased and continued until 2002.

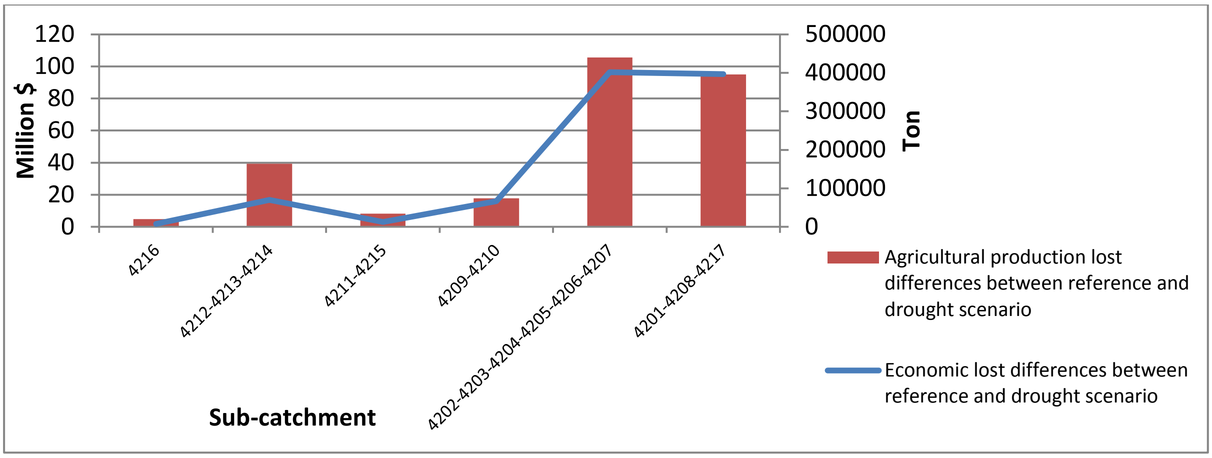


Figure 5.7: Reduction of crop production and production income under the drought scenario for the sub-catchments

APPENDIX V: Table referred to in Chapter 6

Table 6.1: Information concerning the models and simulations names which use to projection of climate change

Modeling center	**model names**	**Institution**	**Terms of use**
CSIRO-BOM	ACCESS1-0 model ACCESS1-3	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia)	unrestricted
BCC	bcc-csm1-1	Beijing Climate Center, China Meteorological Administration	unrestricted
GCESS	BNU-ESM model	College of Global Change and Earth System Science, Beijing Normal University	unrestricted
CCCma	CanESM2 model	Canadian Centre for Climate Modelling and Analysis	unrestricted
NCAR	CCSM4 model	National Center for Atmospheric Research	unrestricted
NSF-DOE-NCAR	CESM1-BGC CESM1-CAM5	National Science Foundation, Department of Energy, National Center for Atmospheric Research	unrestricted
CMCC	CMCC-CM CMCC-CMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici	unrestricted
CNRM-CERFACS	CNRM-CM5	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	unrestricted
CSIRO-QCCCE	CSIRO-Mk3	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence	unrestricted
EC-EARTH	EC-EARTH	EC-EARTH consortium	unrestricted
LASG-CESS	FGOALS_g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences; and CESS, Tsinghua University	unrestricted
FIO	FIO-ESM	The First Institute of Oceanography, SOA, China	unrestricted

Table 6.1: Countinued

NOAA GFDL	GFDL-CM3 NOAA GFDL GFDL-ESM2G, RCP8.5 NOAA GFDL GFDL-ESM2M, RCP8.5	Geophysical Fluid Dynamics Laboratory	unrestricted
NASA GISS	GISS-E2-H GISS-E2-H-CC GISS-E2-R GISS-E2-R-CC	NASA Goddard Institute for Space Studies	unrestricted
MOHC (additional realizations by INPE)	HadGEM2-AO HadGEM2-CC HadGEM2-ES HadCM3 HadCM3Q	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	unrestricted
INM	inmcm4	Institute for Numerical Mathematics	unrestricted
IPSL	IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR	Institut Pierre-Simon Laplace	unrestricted
MIROC	MIROC5 MIROC-ESM MIROC-ESM-	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	unrestricted

Table 6.1: Countinued

	CHEM		
MPI-M	MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M)	unrestricted
	MPI-ESM-MR		
MRI	MRI-CGCM3	Meteorological Research Institute	unrestricted
NCC	NorESM1-M	Norwegian Climate Centre	unrestricted
	NorESM1-ME		

The mean monthly precipitation and temperature changes are indicated in Figure 6.1. The figure shows that the temperature is predicted to rise under the RCP 8.5 scenario for all months. However the variability of the precipitation projection is significant. The climate model predicts increased monthly precipitation from July to September; while for other months it predicts a decreased precipitation.

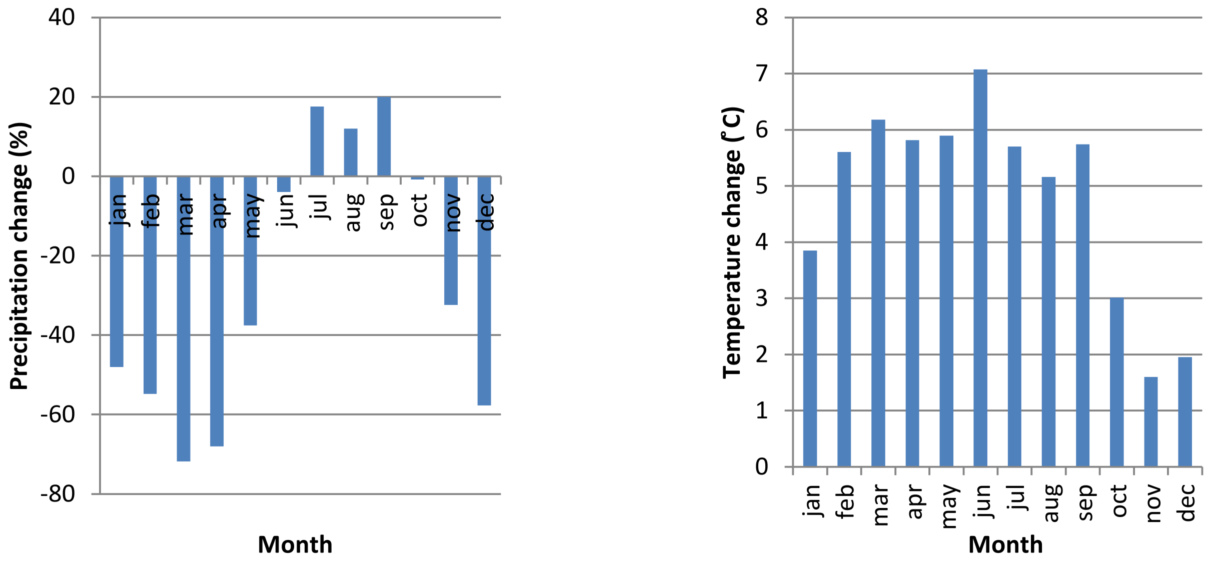


Figure 6.1: Projected mean monthly precipitation and temperature averaged change for the four stations under RCP8.5 scenario by 2006-2100

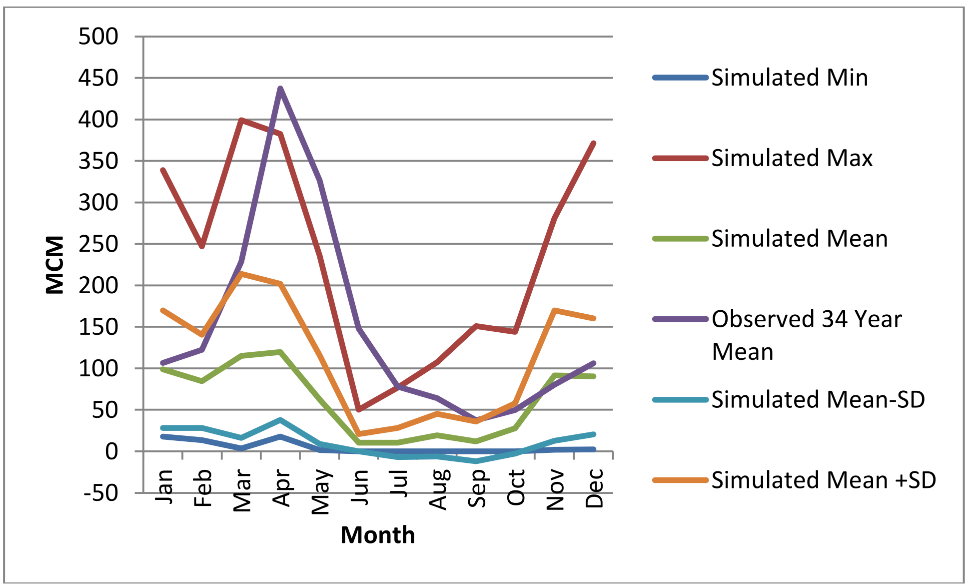


Figure 6.2: Simulated Mean, Maximum, Minimum, One Standard Deviation and historical Mean monthly stream flows.

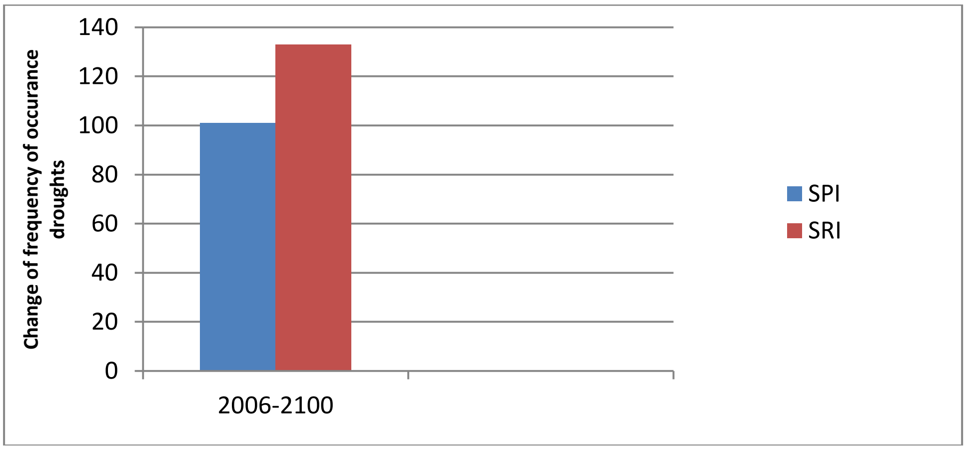


Figure 6.3: Change of frequency of meteorological and hydrological drought events of intensity 1<1 from baseline (with duration of 6months)

In Figure 6.3, the extension of climate change impact on meteorological drought to hydrological drought can be analysed. The figure shows the change from baseline (1971-2005) in the number of drought events with duration of 6 months. The frequency for meteorological drought with duration of 6 months will increase too 100 for fuure time period (2006-2100). Also the frequency for hydrological drought with duration of 6 months will increase too 135 for fuure time period (2006-2100).

Table 6.2: Statistical result of flow with and without human abstractions

	Flow without human abstractions	**Flow with human abstractions**
Mean	1021.24	485.63
Median	952.12	450
Standard deviation	449.30	287.75
Max	2271.03	1286
Min	235.99	35.53
First quartile	667.18	279.12
Third quartile	1263.88	624.099
CV	0.43	0.60

Table 6.2 shows that the mean and maximum of flow without human abstraction is about two times more than mean of flow with human abstraction. However, the minimum of flow with human abstraction is about six time more than flow without the human abstraction. Also the coefficient variable of flow with human abstraction is significantly higher than (1.37 times more than) flow without human abstraction. So it shows dispersion of each point in the data series around the mean is high in flow with human abstraction.

APPENDIX VI: Figures referred to in Chapter 7

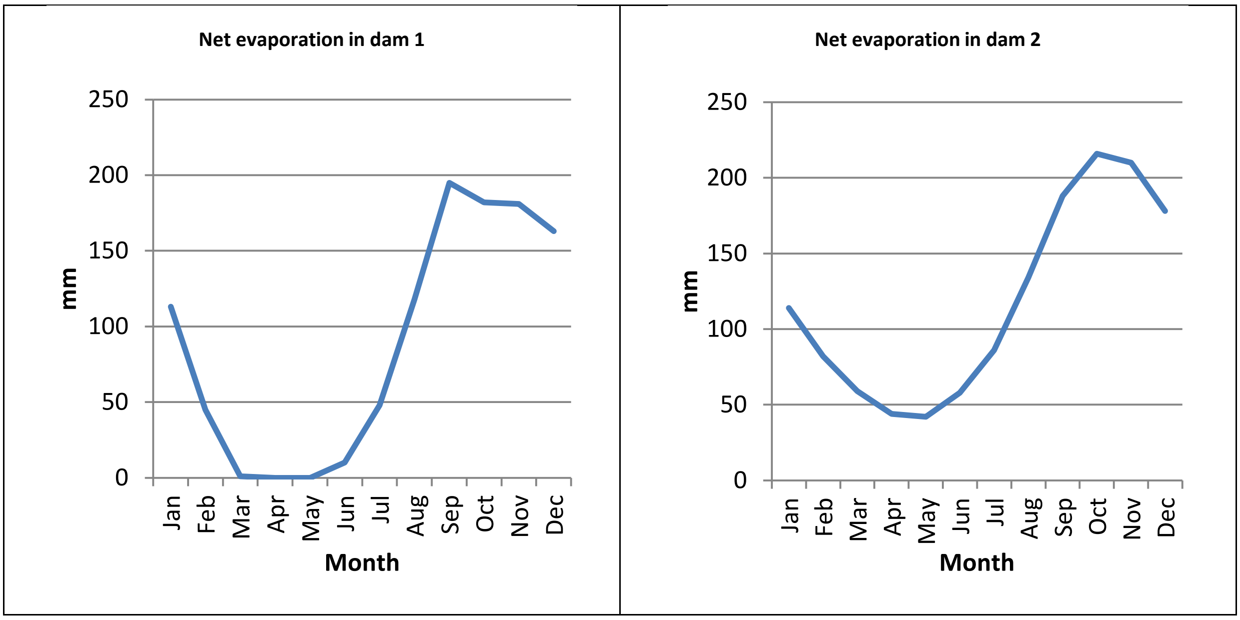


Figure 7.1: Monthly net evaporation in the conceptual dams for adaptation scenario in future

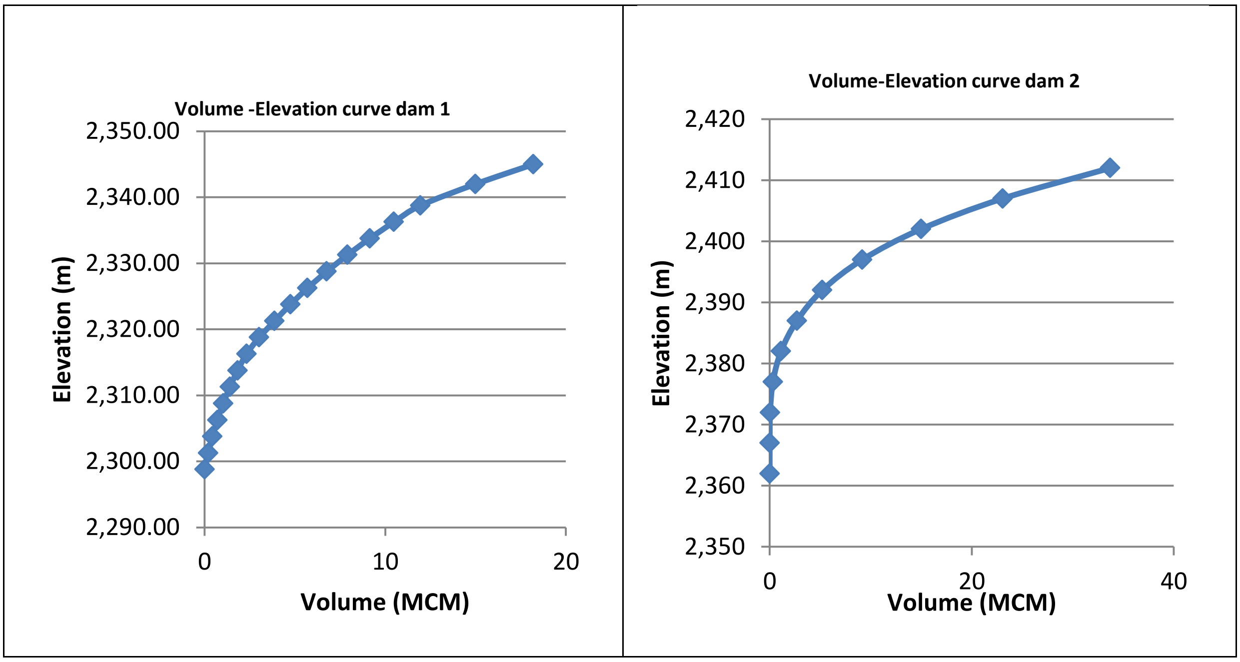


Figure 7.2: Volume-Elevation curve in the conceptual dams for adaptation scenario in future

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